The following chapter is correct, but is missing some information and pictures. It will be updated at a future date.

Chapter 7: Beam Transport Lines

I'd like to be
Under the sea
In an octupoles' garden
In the shade

Main Ringo

The purpose of the beam lines is to transport protons and antiprotons from one accelerator to another, or to the Fixed Target experiments. The beam lines to be discussed in this chapter include the MI-8 line, which delivers protons from the Booster to the Main Injector; the abort line, in which protons are kicked out of the Main Injector to a beam absorber; the P1 line, which serves as a connection between the Main Injector and the Tevatron or other beam lines; the P2 line, which transports beam towards the Antiproton Source and the Fixed Target experiments; the A1 line, which transfers antiprotons from the Main Injector to the Tevatron; and NuMI, which sends protons to an external target and ultimately neutrinos to Minnesota. (These beamlines are sometimes given alternate names—the P1 line is sometimes referred to as the P150 line, and the A1 line is also known as the A150 line, because transported beam in those lines is often at 150 GeV.) The P3 line will not be discussed in detail in this book, because it is remote from the Main Injector ring and should more properly be thought of as a dedicated beam line to the Fixed Target experiments. Sometimes, the P2 and P3 lines are collectively named the Main Ring Remnant, since most of the magnets were once part of F Sector in the Main Ring.

All of the beam lines have some things in common: for one, any given pulse of beam only passes through them once. This simplifies their design, because there is no need for any of the devices specifically needed for circulating beam, such as sextupoles, octupoles, or RF. It also makes possible the use of beam-intrusive instrumentation, such as multiwires, which can survive one hit of beam each cycle but not the tens of thousands of hits they would have to sustain if they were in the circulating beam.

In a general way, all of the beam lines also share a common process for transferring beam from one machine to another. Kickers—very fast but relatively weak magnets—deflect the beam in order to position it with respect to a septum magnet. A magnetic septum has one aperture with a magnetic field, and another aperture that is allegedly field-free. It can be thought of as a way to place a beam pipe and a magnet next to each other when there is not enough room for them to coexist as separate components. The kicker determines which aperture the beam enters. Normally (but not always), the kicked beam enters the field region of the septum and is bent into the beam transport line, while the circulating beam passes through the field-free region. The specific type of magnetic septum found almost universally in the Main Injector beam lines is called a Lambertson magnet, named for its inventor.

When beam is being injected into an accelerator from a beam line, the sequence is reversed—a Lambertson magnet bends the beam onto the appropriate trajectory, and then a kicker corrects the angle so that everything is on the proper orbit.

The beam sync clock initiates the very precise timing required by the kickers. Beam sync events are responsible for injection timing as well as extraction timing.

Kickers

Magnet Construction

Kicker magnets are unique because they have to be very fast. Beam that is being injected into or extracted from a machine has to be deflected without affecting any beam that is already circulating. Beginning with zero current, a kicker magnet has to achieve full current quickly—usually within a microsecond or less—and remain at a steady current until all the beam has passed through. Often, the current must then be removed from the kicker within a very short time to prevent subsequent beam from being kicked.

Some of the kickers, such as those in the abort line and P1 line, must be prepared to deflect beam at a variety of energies. In contrast, the injection kicker at the end of the MI-8 line and the kickers for transfer in and out of the Recycler only need to deal with 8 GeV beam, and the kicker at MI-62 for extracting antiprotons to the Tevatron always operates at 150 GeV. For all of the extraction kickers, the object of the game is to get the beam into the field region of a Lambertson magnet; injection kickers generally accept beam from a Lambertson magnet.

Since the inductance of a magnet limits the speed at which the field can change, kickers are built with a single "turn;" there is no coil as such. The current only makes one pass through the magnet. The field generated by the current is amplified by sections of ferrite surrounding the beam pipe. Unfortunately, the absence of a coil also means that a kicker magnet is relatively weak, so the beam trajectory must be adjusted to minimize the amount of deflection required.

For the following discussion, refer to Fig. 7-1, which is a block diagram representing a generic kicker power and control scheme. Variations on this theme will be discussed as the tour of the various beam lines progresses.

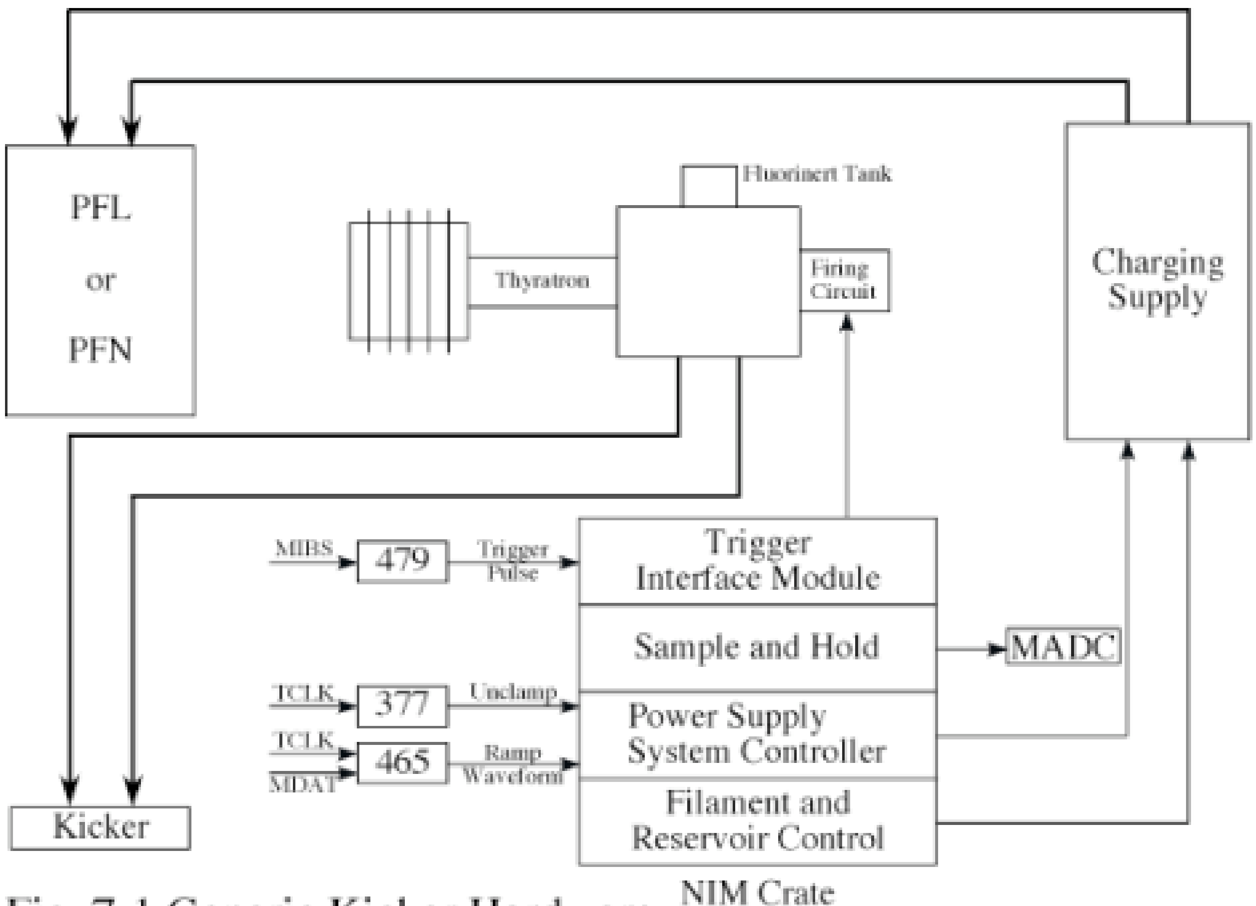


Fig. 7-1 Generic Kicker Hardware

PFNs and PFLs

The current in a kicker magnet is at a very high level for a very short time. Energy is dissipated in the magnet faster than it can be supplied, so a mechanism is required to store energy and then release it at the proper time. A charging supply feeds charge into a resonant system and the energy is stored in the capacitance and inductance of the system. In a Pulse Forming Network (PFN), the capacitors and inductors exist as discrete components; in contrast, a Pulse Forming Line (PFL) uses the “natural” inductance and capacitance of a large (RG-220) cable. After a PFN or PFL is fully charged, a trigger event allows the energy to be discharged into the system at the proper time.

However, if the energy in a capacitor or inductor were to be discharged directly into a magnet, the current would start out high and decay exponentially—the strength of the magnetic field would decline significantly over the interval of time that the beam is present. Instead, a waveform is required that is flat through the duration of the beam pulse. A PFN gets around the problem of exponential decay by modularizing the capacitor/inductor units—the greater the number of modules the closer the current waveform will approximate a square wave. The ideal square waveform is flat on top, with nearly instantaneous rise and fall times. In contrast, a PFL is designed so that the inductance and capacitance of a cable acts as a continuum of infinitesimal “modules;" here, the waveform can also be made flat, but for a shorter period of time. PFLs are adequate for the duration of a Booster batch (2.2 microseconds). PFN's are found at locations where several consecutive batches needed to be kicked, as during Fixed Target mode.

The charging supply is usually a Spellman or Glassman module. The module itself usually runs around 3 KV or so, but the charge that it delivers to the PFN or cable can produce voltages in the tens of kilovolts. The supply is controlled via a NIM-based “Power Supply System Control” module. Of course, the system must be charged to a specific voltage, so a reference voltage is sent to the control module via a CAMAC card. If the beam energy is constant, a CAMAC 118 or 119 card will do—these cards establish a DC reference. If the kicker voltage must track changing beam energy, a C465 card is required. The kickers at MI-10 use C118 cards, those at MI-62 use C119 cards, and those in the abort line and at MI-52 use C465 cards.

To save wear and tear on the hardware, the supply is “clamped” down until an unclamp event is sent to the controller. The unclamp event is sent from a C377 card and is usually referenced to a Main Injector reset-specific event (say, a $2B). When the controller receives the event, the supply begins to charge, tracking its reference.

Thyratrons

It takes longer to charge up a PFN or PFL than it does to discharge into the kicker magnet. A Thyratron is a massive switch—actually, a tube—that isolates the PFN or PFL from the kicker magnet until it is time to fire. Generally, hydrogen, or its isotope deuterium, serves as the charge carrier. When the Thyratron is triggered, and the charge carrier begins to conduct, the system "avalanches" as charge is suddenly transferred from the PFN or PFL into the magnet.

Thyratrons are equipped with a reservoir, which can be used to adjust the sensitivity of the Thyratron tube. If the reservoir is set too high, the Thyratron may discharge spontaneously before receiving a trigger, and the system will not be ready when the beam arrives. If the reservoir is set too low, the Thyratron may not fire at all.

Triggers

Ideally, the trigger pulse to fire the Thyratron should be set just early enough so that beam arrives immediately after the current has reached full value. The timing must be accurate to within a few nanoseconds. The Trigger Interface Module, in the same NIM crate as the Power Supply Control Module, generates the pulse that triggers the Thyratron and fires the kicker.

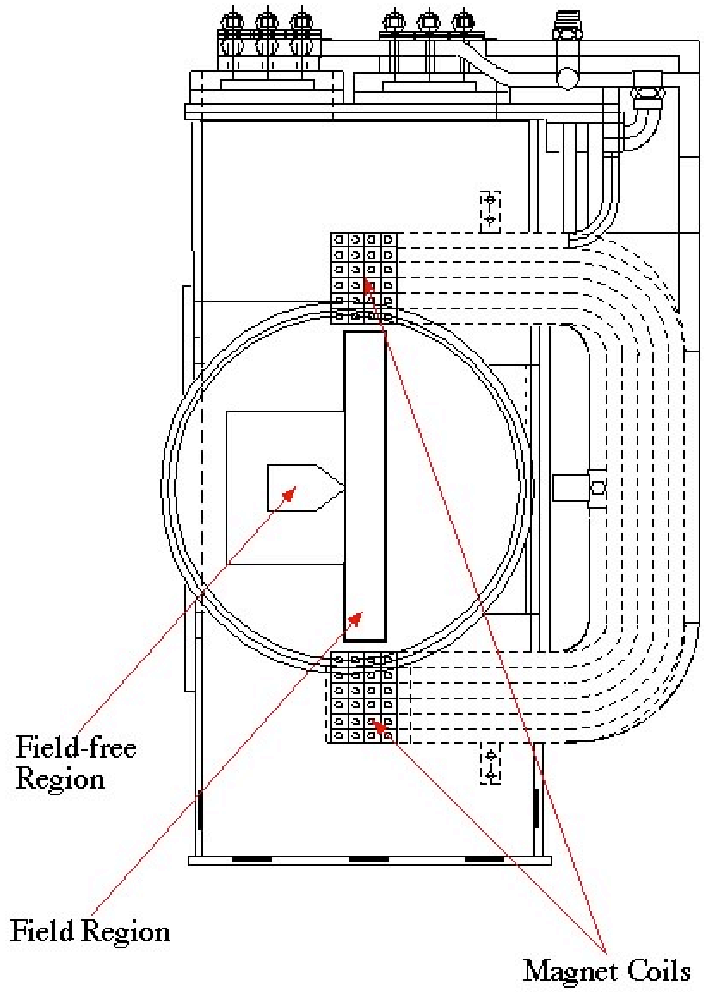
In most cases, the ultimate source for timing the trigger comes from the beam sync clock. (The MIBS clock is ultimately generated by a collaboration of the RF systems and the Time Line Generator, and correlates events by counting RF buckets.) Locally, a C279 or C479 decoder card is "armed" by the beam sync transfer event, and sends the pulse to the trigger module after a predetermined delay counted in RF buckets. (In contrast, note that the timing of the unclamp event does not require a great deal of precision, as long as the kicker is fully charged by the time it fires. A delay from a TCLK event is close enough. The trigger event, on the other hand, requires the precision of the beam sync clock.)

Finally, a TCLK "reflection" event is created simultaneously with the broadcast of the beam sync event. The reflection event comes in handy for such things as beam diagnostics or sequencer steps, since hardware capable of decoding TCLK can already be found at nearly every location. For example, the Tevatron sequencer listens to reflection events to confirm that a beam transfer attempt has just taken place.

More information about beam sync clocks can be found in the Controls Rookie Book, or in the mythical Controls chapter of this book.

Lambertsons

The Lambertson magnets, according to local Fermilab definition, have a field-free aperture and an aperture with a magnetic field, in close proximity to each other. The Lambertson design shown in Fig. 7-2 is used in the P1, A1, NuMI, and abort lines, as well as injection into the Tevatron. The lattices for all four lines are similar, except that the Lambertson in the abort line is “wired” upside-down so that beam is extracted downward; the other beam lines bend beam up from the Main Injector ring.



Lambertson magnets have a field region and a field-free aperture. In the beam transfer lines, circulating beam passed through the field-free region. Extracted or injected beam passes through the field region, where it is deflected. This particular design is used for the abort line, P1 line, NuMI, and the Tevatron injection.

Fig. 7-2 Lambertson Magnet

Another difference among the various lines is that the abort line and the P1 line must be able to extract beam at a variety of energies between 8

GeV and 150 GeV, while NuMI and the A1 line extract at a constant energy (120 GeV and 150 GeV, respectively). At 120 or 150 GeV, three of the relatively powerful Lambertsons are needed to produce a vertical deflection large enough (at least 3.5 inches) to clear the Main Injector beam pipe and cleanly enter the extraction pipe. Extraction kickers displace the beam horizontally into the field region of the Lambertson—but remember that in the Main Injector, the main quadrupoles are closer together than, say, in the Tevatron. This high packing ratio, or relative density of quadrupoles, helps circulating beam by keeping its size small, but it also leaves less room between them for the extraction devices. Only two of the three Lambertsons will fit between a pair of quadrupoles, the remaining one being placed upstream (Fig. 2-8 shows the basic lattice types that the extraction devices must fit into).

This arrangement works at 150 GeV, where the beam size is small and the beam is hard to bend. However, at 8 GeV, the beam has a larger cross-section and must be deliberately steered further out horizontally in order to avoid the septum of the upstream Lambertson (peek ahead to Fig. 7-22). To immediately deflect the beam vertically would guarantee that a great deal of it would be scraped off in the quadrupole, with its tighter vertical aperture. To avoid those losses, the role of the upstream Lambertson has to be minimized or eliminated at 8 GeV. The abort and P1 lines use different strategies to deal with this problem; those strategies will be described in later sections.

A BPM horizontal display frame of the ring reveals the locations of most of the Lambertsons, since the beam is bumped around the septum between the field and field-free apertures.

New and Used Magnets

The beam lines are a haven for magnet refugees arriving from decommissioned accelerators and the older beam lines. Design tolerances are often less stringent for straight-through beam as opposed to circulating beam, and, where feasible, money can be saved by recycling old components. Other magnets are new, but based on older designs.

Main Ring Large Dipoles

The large dipoles taken from the old Main Ring performed the same general function as the main dipoles in the Main Injector. The major differences between the two types are that the coils are smaller in cross-section, requiring more turns, and that the beam pipe through the Main Ring magnets is rectangular rather than elliptical.

There were three major types of large dipoles in the Main Ring: B1, B2, and B3. Most were either B1 or B2 dipoles. The B1 magnets had a larger horizontal aperture (1.5”X5”), while the B2 magnets had a relatively larger vertical aperture (2”X4”). This is because of where they were located in the lattice—there would be two B1 dipoles to either side of the horizontally focusing quadrupoles, and two B2 dipoles would be placed to either side of the defocusing quads. (Remember that beam is biggest horizontally at the focusing quads, and vice-versa.) That pattern is still intact through the P3 line, which of course is part of the Main Ring remnant. In most of the other beam lines where large dipoles are needed, only the B2 magnets are used—the magnets are often rotated, and the B2 magnets provide the best overall aperture in both planes.

The different vertical gap sizes of the B1 and B2 dipoles means that in order to maintain the same overall field strength, the B1 dipoles must have 12 turns while the B2 dipoles need 16 turns.

There were several B3 dipoles in the Main Ring, used primarily in the overpasses that bent the beam up and over the detectors at CDF and D0. The B3 magnets have an aperture of 3”X5”. Two of these industrial-strength dipoles have been incorporated into the MI-8 line; the other is at the end of the P2 line, where the AP-1 line branches off toward Pbar.

EPB Magnets

“EPB” stands for “Extracted Proton Beam.” These magnets were originally used in the Fixed Target beam lines. The design of the dipoles is similar conceptually to the large dipoles described above, but smaller and shorter. In cross-section, they are 12.5” high and 16” wide and either five feet or ten feet long.

Newly built quadrupoles based on the EPB model are the "3Q120" (10 foot) and "3Q60" (5 foot) magnets; the design of the manifolds and steel laminations has been modified from the original.

Some superfluous technical information on EPB magnets can still be found in the Switchyard Rookie Book.

C-Magnets

C-magnets are one degree of separation beyond the Lambertsons. The beam pipe is just far enough away from the magnet to allow the two to be separate components. The “C” designation refers to the shape of the magnet, which surrounds the beam tube on three sides. C-magnets are found just downstream of the Lambertsons in several of the beam lines; extracted beam passes through the magnet, while circulating beam goes through the external pipe.

Correction Dipoles

Horizontal and vertical trim dipoles have been liberally interspersed among the other beam line components. Some of these correctors are recycled from the Main Ring, and others are of the newer Main Injector type.

Many of the corrector dipoles are from LEP (the now decommissioned Large Electron-Positron collider at CERN). These ugly magnets with the lead-based green paint were sold to Fermilab at a dollar apiece, and are probably overpriced. The dipole field is generated by a single coil and is shaped by two plates; beam passes between the plates. Their advantage: they are cheap and available. Their primary disadvantage: they have high inductances and cannot be used for applications that require rapid changes in the field strength. They are used primarily in the MI-8 line and A1 line.

More Quadrupoles

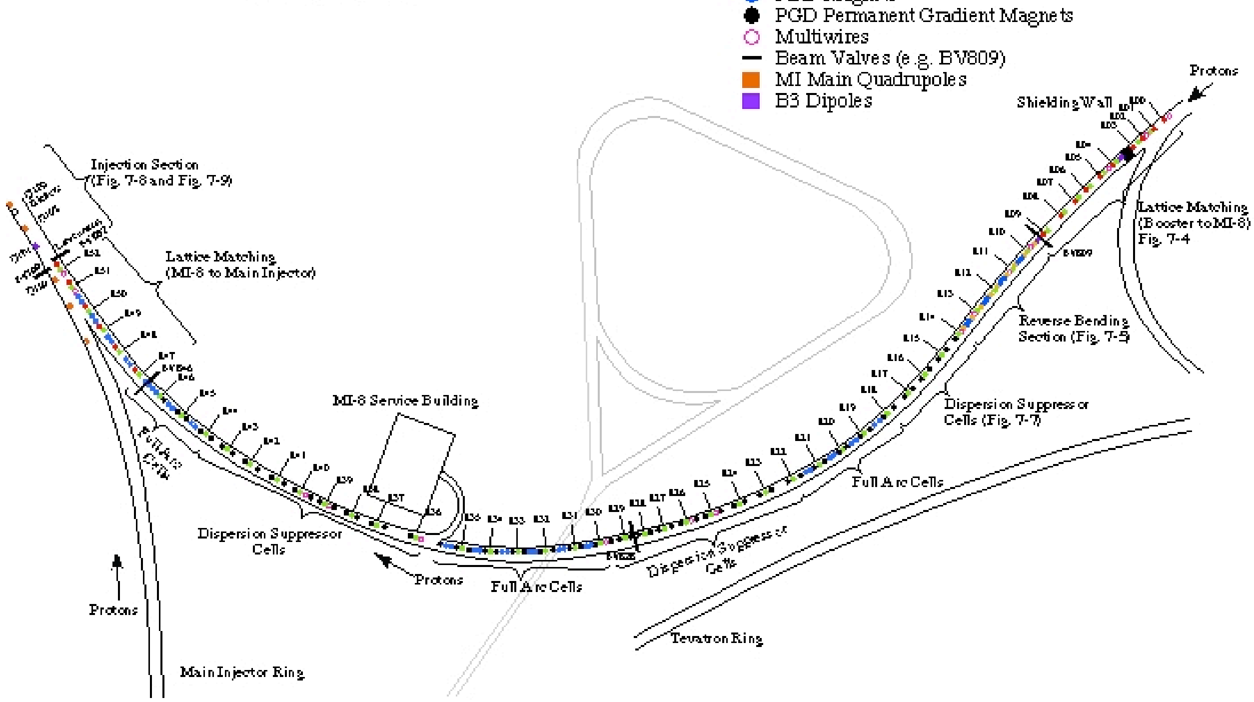
The SQ quads were originally built for the Antiproton Source and the old 8 GeV line. A number of those magnets from the 8 GeV line have now been recycled for use in the MI-8 line.

Some of the 84" quads from the Main Ring have been relocated to various Main Injector beam lines.

The MI-8 Line

The MI-8 line (Fig. 7-3) transports 8 GeV protons from the Booster to the Main Injector ring. The path is somewhat convoluted for two reasons.

Fig. 7-3
MI-8 Line



Vertically, the Main Injector ring is about 11 feet below the level of the Booster ring (Fig. 7-4). Horizontally, the line must avoid the pre-existing Antiproton Source, although it must still pass under the Transport Enclosure.

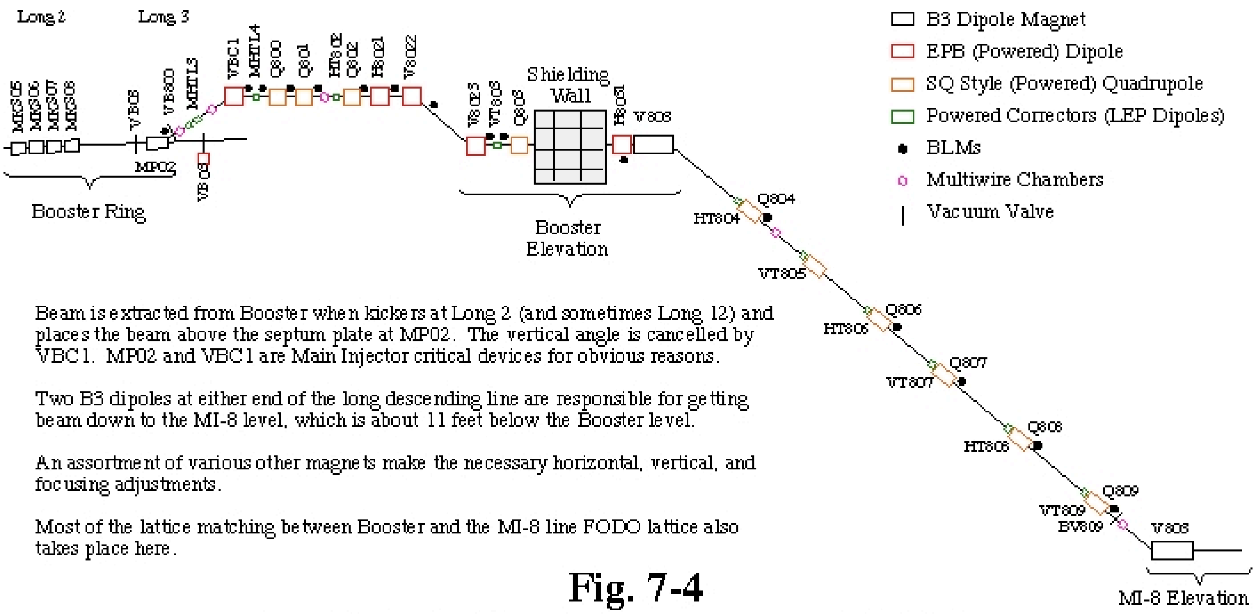


Fig. 7-4
Vertical Profile of Upstream of MI-8 Line

Most of the MI-8 line is composed of permanent magnets. Originally, the line was designed to use powered magnets, but it became a testing ground for the permanent magnet concept when the Recycler was in the earliest stages of development. Large powered magnets are still used at the beginning and end of the line, and LEP dipole correctors are used throughout the line.

The details of extraction from the Booster are included in the Booster Rookie Book. Essentially, in its simplest form, the four kickers (MKS05, MKS06, MKS07, and MKS08) at Long 2 give the beam an upward kick so that extracted beam passes over the septum plate of MP02 at Long 3. The beam leaves Booster at a tangent to the Booster ring horizontally and at an upward angle vertically. There are kickers at Long 12 as well; their purpose is to send beam to the Long 13 dump or to the Radiation Damage Facility (RDF). To create partial batches, used for coalesced beam in Collider mode, a few bunches are sent to the Main Injector and the rest are sent to the Long 13 dump.

Numbering in the line begins with "800" at the point at which the beam leaves the Booster, and ends at "852," where it enters the Main Injector. In its entirety (Fig. 7-3), the MI-8 line looks rather complicated, but in reality there are only five different kinds of lattice sections to worry about. The stretch through the middle is your basic FODO lattice, and the two at either end are the matching lattices. Since the Booster, MI-8 line, and Main Injector ring each have a unique lattice, the transition from one to the next has to be done in a controlled fashion. There is a Booster matching lattice at the beginning of the line and a Main Injector matching lattice at the end. Background information on lattice functions can be found in Chapter 2.

Most of the FODO lattice in the MI-8 line consists of two alternating lattice types—the beam is gradually being bent to the right through this region—but just after the Booster matching section is a short length of reverse bending, in which beam is bent to the left so that the line is steered away from the Pbar rings. In order of appearance:

The Booster Matching Lattice

The region between 800 and 809 (Fig. 7-4) is dedicated to making the transition between the Booster lattice and the MI-8 FODO lattice, but there are also important things happening vertically and horizontally.

Although most of the MI-8 line consists of permanent magnets, the magnets in the Booster matching section are powered. The quadrupoles are SQ-style electromagnets similar to those found in the Pbar beam lines; there is one quadrupole at each numbered location, and the even/focusing, odd/defocusing convention is applied here as in the Main Injector ring. The purpose of the matching quadrupoles is to convert the lattice functions (dispersion as well as the amplitude and phase of the beta functions) in Booster to that of the FODO lattice of the MI-8 line. Within the matching section, the amplitude of the beta function varies from cell to cell until the FODO lattice is reached.

Within this section of the line, the vertical path dominates the scene. The vertical angle out of the Booster from MP02 is cancelled by a 5-foot EPB magnet known as VBC1. The short, level section following VBC1 contains three of the matching lattice quads (Q800, Q801, and Q802), and a 10-foot EPB (H8021) for steering the beam to the left of the AP-4 dump. A dogleg (the picture explains the term best) consisting of the two EPB magnets V8022 and V8023 brings the beam back down to the original elevation it had in the Booster.

(At this point the beam pipe passes through a shielding wall. Why is there a shielding wall in the middle of an enclosure? Once upon a time, when antiprotons were much more difficult to produce, the Antiproton Source was tuned by sending protons, from Booster, into the rings. The line connecting Booster and the Debuncher was known as the AP-4 line. Later, when Collider operations required that partial batches be sent to the Main Ring, the upstream end of the AP-4 line was reworked to send the excess beam to a beam absorber (called a dump in those less sensitive days). The shielded area around the absorber became known as the AP-4 dump. Now that the excess beam is being sent to the Long 13 dump, there is a big pile of concrete blocks surrounding a section of the MI-8 line for no apparent reason.)

After the shielding wall, a B3 dipole recycled from the Main Ring starts the beam down the long slope to the Main Injector elevation 11 feet below. At the end of the slope, another B3 dipole straightens the beam out at the Main Injector level. The two B3 dipoles, which are in series, are collectively known as V803. Although the MI-8 line continues for a considerable distance, V803 is the last major vertical bend in the line. However, at the bottom of the slide the beam is still 35 mm higher than circulating beam in the Main Injector—a fact that will be explained in due time.

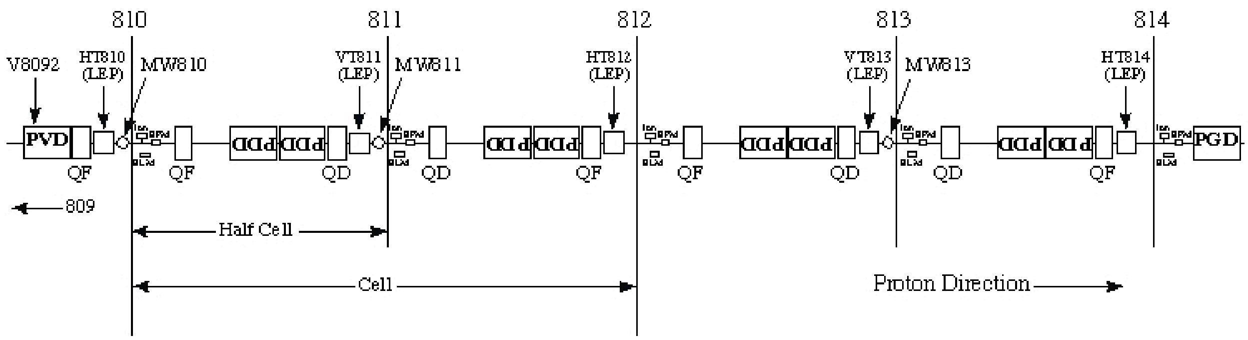
The first horizontal priority in the MI-8 line is to prevent the beam from hitting the enclosure wall and to steer it to the left of the shielding wall. That task is performed by a 10-foot EPB named H8021. After the shielding wall, another 10-foot EPB, H8031, gives the beam another push to the left to position it correctly for the trip down the slope. H8031 is the last major horizontally bending powered magnet unique to the MI-8 line. The bulk of the horizontal bending from that point forward is done by permanent magnets.

LEP correctors precede most of the powered quadrupoles. Since beam in the MI-8 line is always at the same energy, the large inductance of the magnets doesn't matter. The practice of including one powered corrector at every half-cell continues down the rest of the line.

Reverse Bending Section

Background information about permanent magnets can be found in Chapter 2.

At 809, the beam has reached the bottom of the slope and, vertically, can virtually coast into the Main Injector. Horizontally, the beam will soon be bent to the right until its trajectory is parallel to that of the Main Injector at MI-10. However, the dispersion match is not quite complete, and besides, if the rightward bend is started now the beam will intersect the domain of the Antiproton Rings.



The reverse bending section begins at the bottom of the vertical slope at 809. The permanent dipoles have been turned upside-down so that they bend to the left instead of the right. Focusing is done with short permanent quadrupoles. The three trim magnets, from LEP, are powered. The section ends at 814.

The purpose of this section is to steer cleat of the Antiproton source rings (see Fig. 7-4).

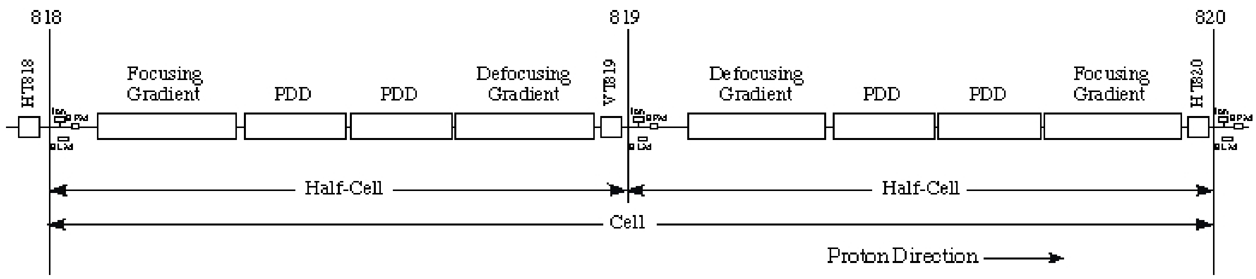
Fig. 7-5
Reverse Bending Section, MI-8 Line

The distance from 809 to 814 (see Figs. 7-3, 7-5) has been designated as the reverse bending section; beam is bent to the left in order to avoid the rings and the surrounding roads. The reverse bending is done by turning the PDD dipole magnets “upside-down;” because most of the MI-8 line bends to the right, the convention—and the labeling—is that the right-bending configuration is “right-side-up.” Right side up in this case means that the magnetic field is pointing up as well (Fig. 2-16).

Focusing in the reverse-bending section is done by two-foot long permanent quadrupoles (Fig. 2-17). The entire reverse-bending section is only two cells long. The focusing and defocusing quadrupoles are identical in construction, but the defocusing quads have been rotated end-to-end with respect to the focusing quads (i.e. they are “backwards”). The section begins with a focusing quad at 810 and ends with a focusing quad at 814. By the end of the reverse bending section, the dispersion match is complete and the trajectory is set up for the long run to the Main Injector.

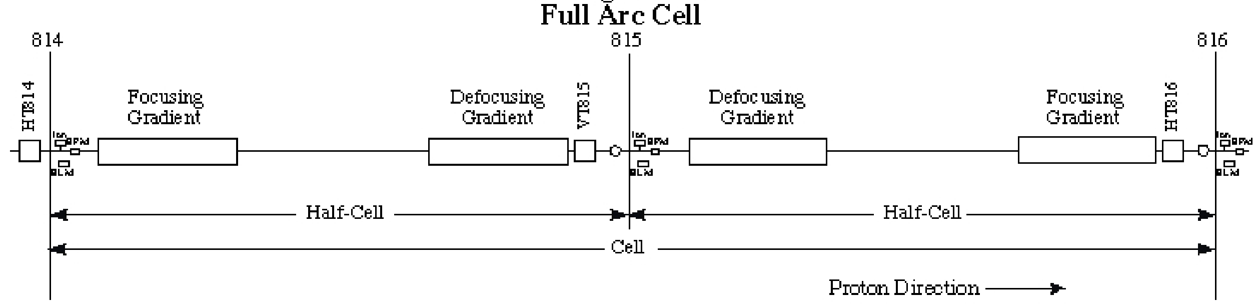
The MI-8 FODO Lattice

The long stretch from 814 through 846 consists of two types of cells: the full-arc cells (Figs. 7-3, 7-6) and the dispersion-suppressor cells (Figs. 7-3, 7-7). Beam is consistently bent to the right in both types of cells, as the beam is brought to an angle nearly tangent to the Main Injector at MI-10.



The full arc-cells begin at 818, 820, 830, 832, 834, 844 and 846. The gradient magnets bend and focus the beam.

Fig. 7-6
Full Arc Cell



The dispersion suppressor cells begin at 814, 816, 822, 824, 826, 828, 836, 838, 840, and 842.

o - Multiwire
IP - Ion Pump
BLM - Beam Loss Monitor
BPM - Beam Position Monitor

Fig. 7-7
"Missing Dipole" Dispersion-Suppressor Cell

The permanent magnets in the dispersion-suppressor cells are all PGD gradient dipoles, while the "full-arc" cells are a combination of PDD "double dipoles" and PGD gradient dipoles.

The PDD magnets are shorter than the PGD magnets, but since the ferrite bricks are stacked two layers deep in the PDD magnets, the two types have the same bending power. Yet another look at Fig. 7-3 shows that the curvature is greater in the full-arc regions. Since this part of the line is populated primarily by permanent magnets, the only control of the beam in this region is provided by the LEP dipole correctors at each half-cell boundary.

The Main Injector Matching Lattice

Location 847, about a hundred meters from the finish line, marks the beginning of the transition to the Main Injector lattice. Powered quadrupoles once again appear at each numbered location, and the oscillations of the beta functions once again change in amplitude. The PGD gradient magnets disappear as the powered SQ-style quads take over the task of focusing. Q852 is the final magnet belonging to the MI-8 line, and the lattice has now been matched to that of the Main Injector (again look at Fig. 7-3).

As of this writing, MiniBooNE magnets have been added to this last stretch of the line. The MiniBooNE line branches out of the Main Injector tunnel before encountering the ring. MiniBooNE extraction will be covered in a future section of this chapter.

Injection into the Injector

Protons at the end of the MI-8 line (Fig. 7-8) are necessarily approaching the Main Injector at a horizontal angle of about 35 milliradians (mrad); it will be seen momentarily that this angle is defined by the bending strength of the Lambertson magnet.

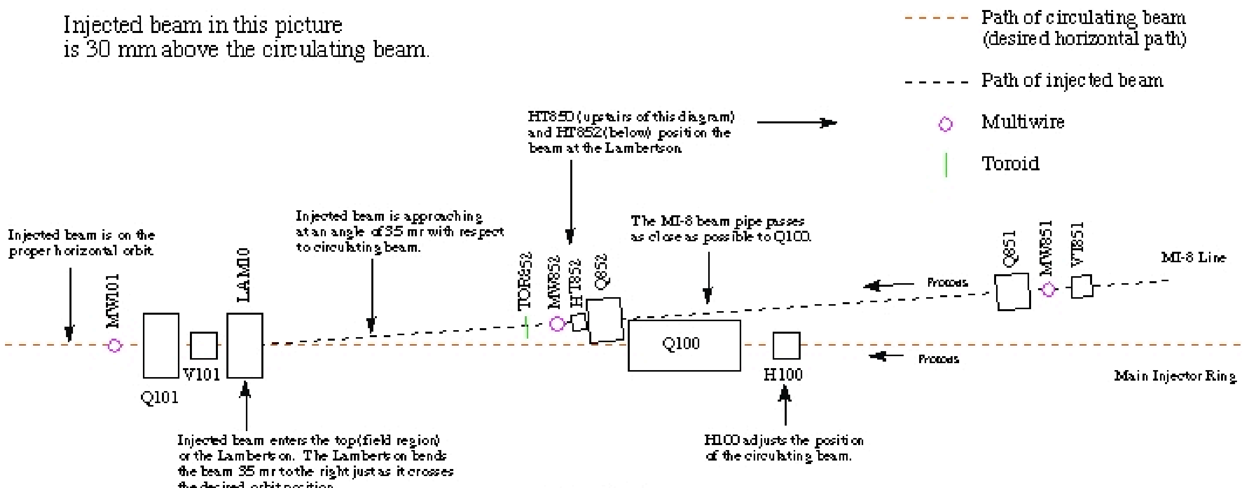


Fig. 7-8
Horizontal Closure in Main Injector
(Top View)

The final bulky component in the MI-8 line, Q852, is placed just downstream of Q100 (in the Main Injector ring) so that the beam line can be set at the 35 mrad angle. Remember from earlier in the line that beam has deliberately been placed about 35 mm above the desired vertical center for circulating beam.

The process of placing injected beam on the proper orbit in an accelerator is called closure. When the orbit is closed, the beam is at the correct position, and angle of trajectory, in both planes. In the Main Injector, the horizontal orbit is closed with a Lambertson magnet, and the vertical orbit is closed with kickers.

The injection Lambertson (LAM10) is located just upstream of Q101, a defocusing quadrupole (V101 is between the two, but doesn't take up much space). The horizontally bending Lambertson has a field region on top and a field-free aperture on the bottom; it was originally built as a spare for the 8 GeV line in the Main Ring. Injected beam was designed to be 35 mm higher than circulating beam and will pass through the top aperture (Fig. 7-9). Beam may already be circulating in the Main Injector, and, if so, will pass through the field-free aperture on the bottom.

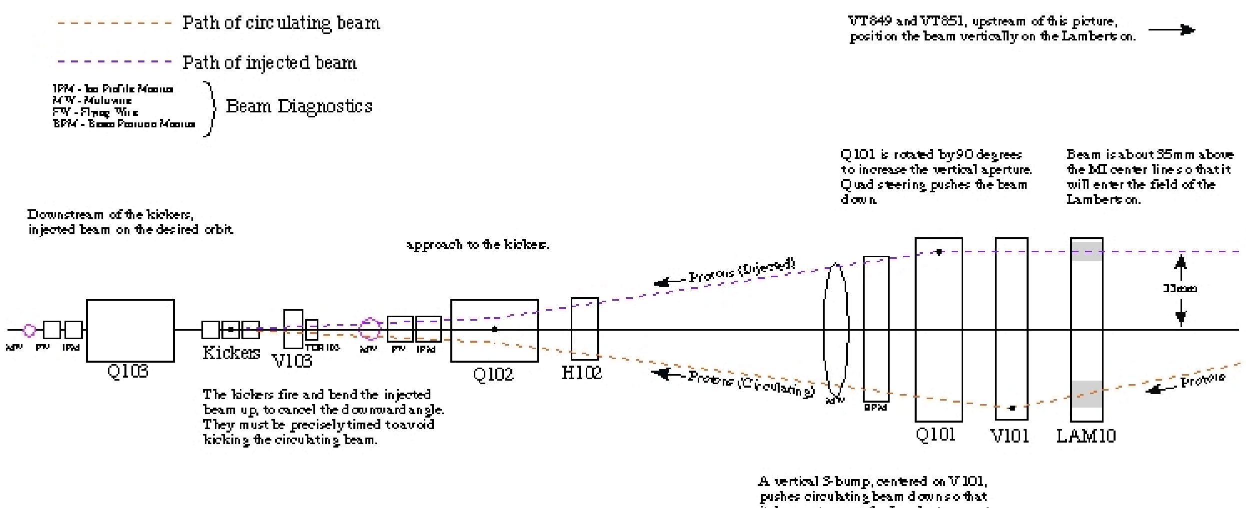


Fig 7-9
Vertical Closure in Main Injector
(Side View)
(Vertical scale grossly exaggerated)

The injected beam in the Lambertson is bent 35 mrad to the right, just enough to offset the angle coming in from the MI-8 line. Since the Lambertson is located at the point where injected beam crosses the closed orbit horizontally, the position and angle are now correct and injected beam is closed in the horizontal plane.

This scheme will only work if the beam actually enters the Lambertson magnet with the correct position and angle of approach. HT850 and HT852, two corrector dipoles in the MI-8 line, are both used to ensure that those two conditions are met.

To close the beam vertically (Fig. 7-9), the beam is deflected onto a downward slope, and the kickers are placed where the beam will cross the desired vertical position. Because of the large vertical separation between the injected beam and circulating beam required at the Lambertson, the kickers are placed as close as possible to where the vertical betatron phase advance is 90˚—the “natural” oscillation of the beam will do much to bring it to the desired vertical position.

Specifically, remember from Chapter 2 that in the Main Injector there is an approximate 90˚ phase advance over the distance between two adjacent “F” quads or two adjacent “D” quads. Beam coming out of the Lambertson is vertically high at Q101 but will have been pushed down by the time it reaches the center of the beampipe at Q103, the next defocusing quad. The kickers are therefore placed as close to Q103 as possible. It is a little more complicated than that, because quad steering—the dipole bending effect resulting from the beam being off-center at Q101—pushes the beam down faster than desired. The correction dipole VT849, in the MI-8 line, can be used to adjust the angle at the Lambertson so that the position is correct at the kickers. The Lambertson is also rolled (rotated) so there will be a slight upward angle imparted to the injected beam.

The orbit of the circulating beam must also be modified, because at 8 GeV the beam is large enough vertically to scrape against the septum plate of the Lambertson. A 3-bump using V641, V101, and V103 pushes the beam down, with the low point being at V101. (A vertical BPM display frame clearly shows this bump.) The Lambertson is close enough to V101 to make it less likely that circulating beam will strike the septum plate

However, because injected beam is high and circulating beam is low, the vertical separation of the injected and circulating beam at Q101 is too large to be accommodated by the aperture of a main quadrupole as normally configured. Q101 has been rolled 90˚ so that the long transverse axis of the aperture is oriented vertically instead of horizontally. Moreover, although most of the other 84” quads from the Main Ring were upgraded with an elliptical beam pipe, Q101 and Q102 were left with the original “star” aperture—giving the beam extra room. (The cross-section of a main quadrupole in Fig. 2-6 shows the elliptical beam pipe surrounded by the four-lobed star aperture. With the elliptical beam pipe removed and the magnet turned on its side, as with Q101, there is much more vertical aperture.) The bus connections are such that it is still a defocusing quad. The two beam trajectories are closer together at Q102, and the beam is wider horizontally; therefore the star aperture is used at Q102 but the magnet has not been rolled.

When the Lambertson closes the beam horizontally, there is the luxury of the injected and circulating beam being in two distinct places—but all of the beam passes through the kickers. The only thing separating injected beam from circulating beam is time, and not very much of that. Timing constraints are very stringent. To kick the injected beam and not the circulating beam, the kickers must have as fast a rise time, and fall time, as possible. The flattop for the kicker waveform is 1.6 microseconds long, which is the length of a Booster batch.

Fig. 7-10, on the next page, illustrates some of the timing and control for the injection kickers. The trigger for the kickers comes from the Booster Extraction Sync (BES), which is itself derived from TCLK. BES, which pre-dates the beam sync clocks, is ultimately referenced to Booster $10 or $12 (beam or pre-pulse) events. A parameter called B:MIEXTR counts down the approximate time before beam is to be extracted. As of this writing, B:MIEXTR has been given a value of 35,450 microseconds. (Remember that although acceleration time in Booster is about 33.333 milliseconds, the Linac and Booster devices require about 2 milliseconds to prepare for beam after the reset has been issued. The exact value of the delay is then determined empirically, after much anguish.) A NIM module in the Booster LLRF room adds the delay to the clock event and then issues the BES.

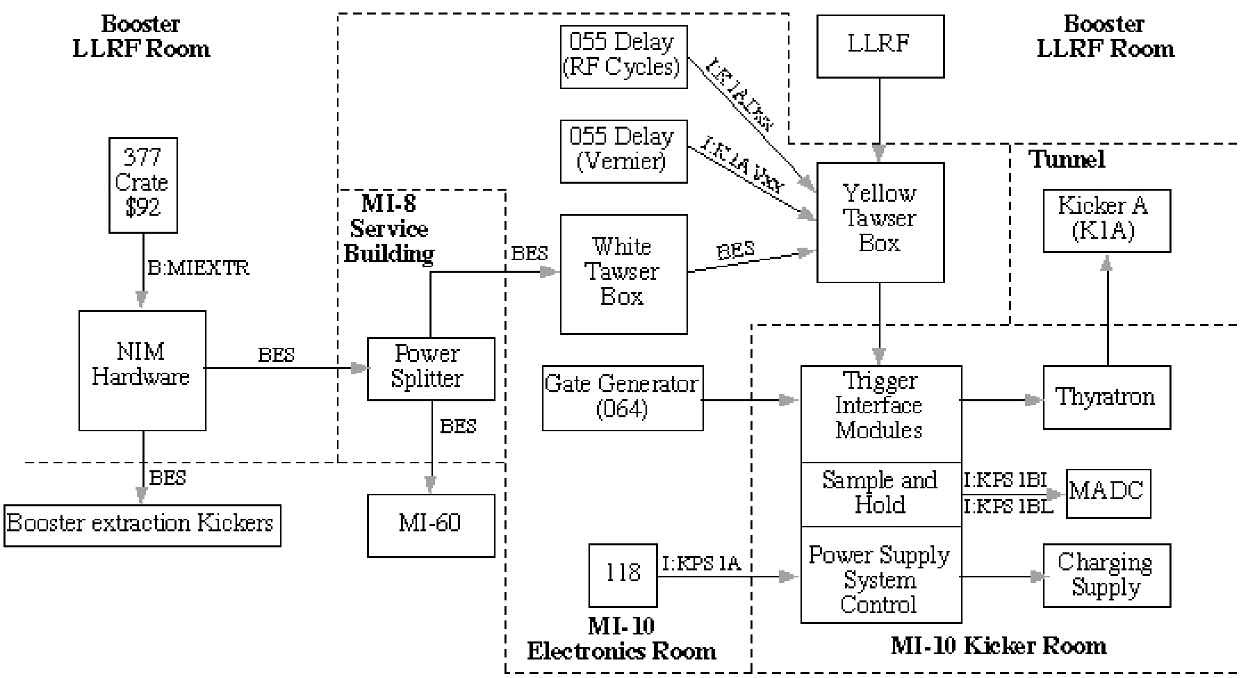


Fig. 7-10, Injection Kicker Timing and Control

The injection kickers in the Main Injector get their timing from the Booster Extraction Sync (BES), which predates the other beam sync clocks. BES is initiated by Booster beam and pre-pulse events ($10s and $12s) and generated by NIM hardware in the Booster LLRF room. The BES signal is fanned out to the Booster extraction kickers, MI-60 and MI-10. The white Tawser box in the electronics room at MI-10 distributes the signal to three yellow Tawser boxer, one of which is shown in this diagram. The yellow Tawser boxes add the RFC and vernier delays to the BES time, using the LLRF as a reference. Finally, the combined signal tells the trigger interface modules exactly when to fire the Thyratron.

A CAMAC 118 card sets the DC level for the kicker voltage. A DC level is sufficient because the beam is always at 8 GeV.

For simplicity, this diagram only shows timing and control for the first kicker, K1A.

BES is used to trigger the Booster extraction kickers as well as the injection kickers at the end of the MI-8 line. A common source for the trigger increases the likelihood that the Main Injector kickers will actually have current in them when the beam passes through. BES is fanned out to the electronics room at MI-10, where it becomes an input to the first Tawser box. The Tawser boxes are named after Stan Tawser, of Tawser box fame.

There is a "White" Tawser box in the electronics room that fans BES out to the three "Yellow" boxes—one for each kicker. The yellow boxes combine the BES, LLRF, and two delays (measured in RF cycles) from nearby 055 cards to create a trigger timing pulse. The pulse is shipped next door to the NIM hardware in the kicker room that triggers the Thyratron.

The delays for the triggers can be found from B4, the Booster Beam Turns Control page (kicker times to LX), and on B19, the parameter page dedicated to Booster extraction. The main type of delay is measured in RF cycles (RFCs); the other, shorter delay is the vernier and is measured in nanoseconds. Both delays are set from 055 cards in Crate $10. It is sometimes difficult to make sense of the numbers, since there is a lot of fine tuning done to compensate for cable propagation delays and kicker rise times.

The injection kicker power supplies reside in the kicker room at MI-10. The pulse is shaped by a PFL, the cables being wrapped around large spools.

MI-8 Power Supplies

The larger powered magnets in the MI-8 line are found at the beginning of the line (800 to 809), and at the end (847 to 852). There are also the small powered LEP dipole correctors at each half-cell. The power supplies for the upstream segment of the line are found in the Booster West Gallery and the Booster West Tower. The corrector dipole supplies for the remainder of the line are located in the MI-8 Service Building. Figs. 7-11 and 7-12 are intended to serve as a complete list of power supplies for the MI-8 line, excluding devices that are actually part of the ring proper. (The magnets themselves have names that may or may not be similar to the ACNET names.) The small box at the upper left corner of each power supply name in Fig. 7-11 (next page) represents the type of CAMAC card controlling the supply; to the right of the box is the type of power supply.

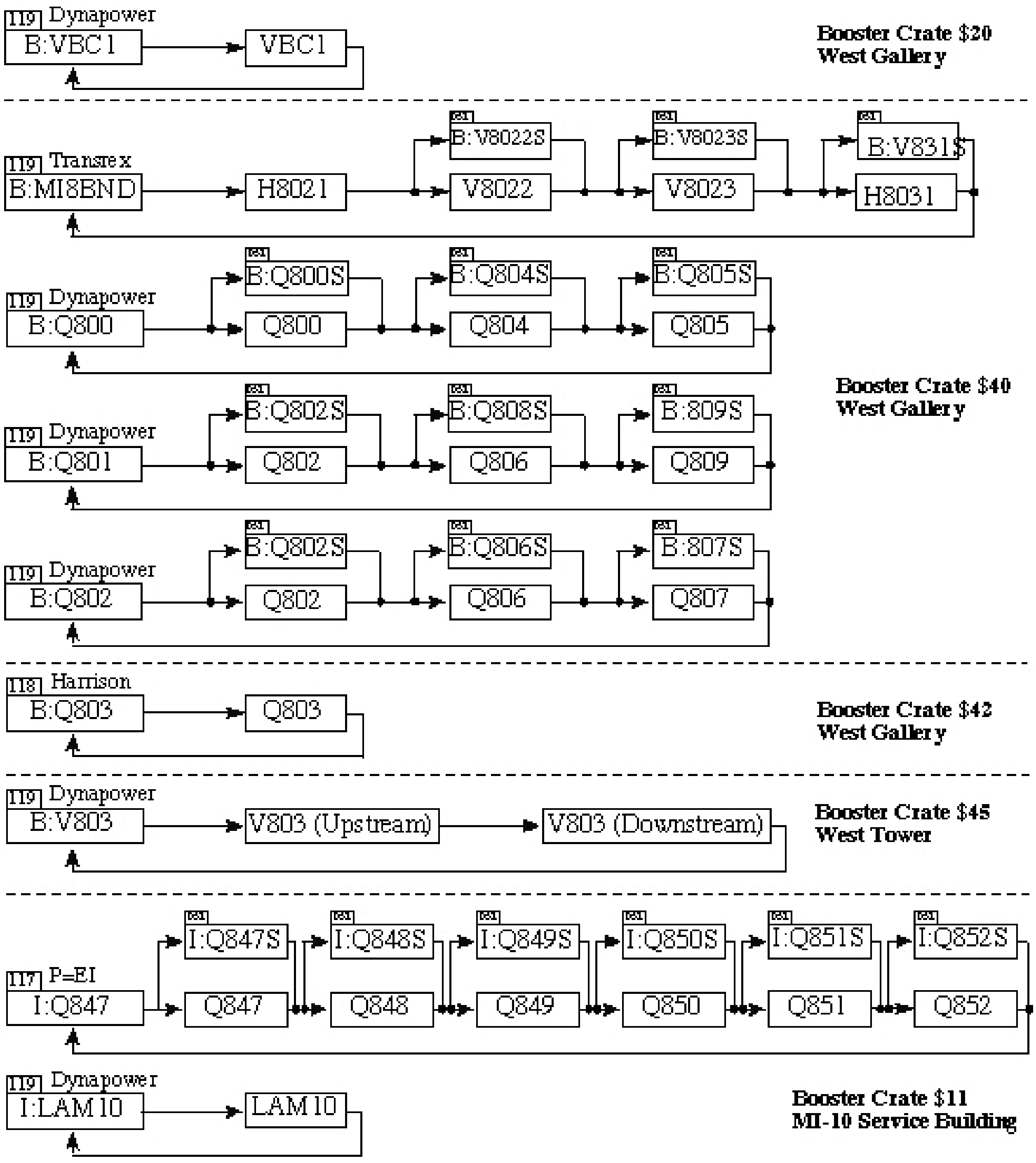


Fig. 7-11 MI-8 Line Power Supplies

Several of the supplies for devices in the MI-8 Line power strings of magnets. Power to individual magnets in a string is customized by diverting some of the current through shunts. The "S" at the end of a parameter designates a shunt.

The number at the upper left of the power supply name represents the CAMAC control card.

Power supplies for the LEP dipole correctors in the MI-s line are listed in Figure 7-12.

VBC1, the first EPB dipole of the line (and a critical device), uses a dedicated Dynapower supply located in the Booster West Gallery. V803, which powers the B3 dipoles at either end of the vertical drop to the Main Injector elevation, uses a Dynapower supply located in the Booster West Tower. These two devices are controlled through CAMAC 118 or 119 cards—cards in the 117,118, and 119 series are capable of sending a power supply an analog reference voltage as well as providing digital control and digital readbacks. Analog readbacks return through MADCs.

Other supplies make extensive use of power supply shunts, where a single power supply drives several devices in series. All of the devices in the series would carry the same current, but some of the current destined for any individual magnet can be bypassed, or shunted, around the magnet, thereby reducing its bending strength. The power supply in each case is controlled through CAMAC 119 cards, while the shunt current—an analog signal—is controlled and read back through 052 cards. ACNET names for the shunts consist of the magnet name followed by an “S;” for example, I:Q804S shunts current around the magnet Q804, which is in series with other magnets that may need to run at different currents. The current in the magnets themselves is calculated by subtracting the shunt current from the primary current; the calculation is done by a disembodied “open-access” front end called BOOSTR that runs on CFSS (one of the central VAXs). The parameter name for the calculated current ends with "I," e.g. "Q804I."

> In the upstream MI-8 line, four power supplies use shunts. B:MI8BND powers four EPB dipoles: H8021, V8022, V8023, and H8031; the last three of these have shunts. The Booster matching lattice contains three quadrupole supplies, each supply powering three magnets: B:Q800 powers Q800, Q804, and Q805; B:Q801 powers Q801, Q808, and Q809; and B:Q802 powers Q806 and Q807.

The LEP magnets, distributed throughout the line, use CPS bulk supplies and regulators identical to those used in the Main Injector ring (Fig. 7-12). I:CPSBW, in the Booster West Tower, powers I:HT800D through

I:HT812D. Although 453 cards control the regulators, the correctors run DC—the ramp tables are not populated, and even if they were, the ramps are disabled. The "D" at the end of the parameter name stands for "DC."

Corrector Power Bulk Supplies	Corrector Dipoles			
I:CPSBW	I:HT800D	I:VT809D		
	I:HT802D	I:HT810D		
	I:VT803D	I:VT811D		
	I:HT804D	I:HT812D		
	I:VT805D			
	I:HT806D			
	I:VT807D			Booster Crate $45
	I:HT808D			Booster West Tower
I:CPSM8	I:VT813D	I:VT821D	I:VT829D	
	I:HT814D	I:HT822D	I:HT830D	
	I:VT815D	I:VT823D	I:VT831D	
	I:HT816D	I:HT824D	I:HT832D	
	I:VT817D	I:VT825D	I:VT833D	
	I:HT818D	I:HT826D	I:HT834D	
	I:VT819D	I:VT827D	I:VT835D	
	I:HT820D	I:HT828D	I:HT836D	
				Main Injector Crate $85
				MI-8 Service Building
	I:VT837D	I:VT845D		
	I:HT838D	I:HT846D		
	I:VT839D	I:VT847D		
	I:HT840D	I:HT848D		
	I:VT841D	I:VT849D		
	I:HT842D	I:HT850D		
	I:VT843D	I:VT851D		Main Injector Crate $84
	I:HT844D	I:HT852D		MI-8 Service Building

Fig. 7-12 MI-8 Line Dipole Corrector Supplies

All correctors in the MI-8 line are from LEP

The "D" at the end of each parameter name designates a DC value.
Each cluster of four devices represents an individual 453 card.

Compare to figures 3-7 and 7-3.

All of the other correctors, from I:VT813D to I:HT852D, are powered by I:CPSM8 in the MI-8 Service Building.

The quadrupoles of the Main Injector matching lattice, from Q847 to Q852, are all powered in series from a single P=EI supply, I:Q847, located in the MI-10 Service Building. There are shunts for all of the individual magnets.

The Lambertson magnet, LAM10, is powered from a Dynapower supply located in the MI-10 Service Building. The kicker equipment is located in a separate room at MI-10.

The correctors V641, V101, and V103, which create a three-bump at the Lambertson, are part of the Main Injector ring and are powered from I:CPS10.

MI-8 Vacuum

Background information on vacuum systems can be found in Chapter 5.

The MI-8 line can be thought of as being divided into four vacuum sectors (see Fig. 7-3). The first sector stretches from the Booster ring to 809. There are actually three valves that can be used to isolate Booster vacuum from the first sector (Fig. 7-4). MP02 is bracketed by two valves collectively known as VB-03. The two valves are designed to open and close in concert; if MP02 is isolated from the rest of Booster, the MI-8 line is isolated from Booster as well. The third valve, VB-800, is part of the MI-8 line immediately downstream of MP02. Obviously, in order to isolate the MI-8 line from Booster while still allowing circulating beam, VB-03 must be open and VB-800 must be closed. VB-800 can assume a secret identity—on Booster applications pages, it is known as VBMI8.

The next beam valve is BV809, just upstream of V803 at the bottom of the slope.

The MI-8 FODO lattice stretches from 809 to 847. It is broken into two sectors, with a beam valve at 828 (Fig. 7-3). The next beam valve is near the downstream end of 846; it isolates the lattice matching section from the FODO lattice.

The final beam valve in the MI-8 line is between Q852 and the Lambertson.

As in the Main Injector ring, vacuum in the MI-8 line is maintained with ion pumps. The power supplies for the pumps are located in the MI-8 Service Building.

Vacuum in the MI-8 line is ideally in the 10^{-8} range, but tends to be slightly worse in the regions near the numerous multiwires. The multiwires use a G-10 (fiberglass) support; the mesh of microscopically thin fibers tends to trap air, which can then continue to outgas for several months following a pump down.

MI-8 Beam Diagnostics

Background information on beam diagnostics can be found in Chapter 6.

The MI-8 line is, of course, the point where beam first enters the Main Injector. The precision with which the beam is injected has a significant effect on its quality later on, so the MI-8 line is crammed with diagnostics—BPMs, BLMs, multiwires, flying wires, toroids, and ion profile monitors.

BLMs and BPMs in the MI-8 line (Fig. 7-13 on the next page) are generally located at every half-cell boundary, although the stretch from MP02 through 803 is more densely instrumented in order to ensure efficient extraction from the Booster. The locations of many of the BPMs and BLMs can be found in Figs. 7-4 through 7-7.

The BLM hardware in the MI-8 Line, unlike its counterpart in the Main Injector ring, does not use microprocessors to organize the data—cards inside the BLM chassis integrate the losses from each ion chamber and then send the value directly to an MADC. The timing to set the interval of integration comes from nearby 377 cards. CAMAC 190 or 290 cards transmit the MADC values back to the MCR. BLM hardware is located in the Booster West Gallery (B:LMVBCU), the Booster West Tower (B:LM800 through

I:LM822), and the MI-8 Service Building (I:LM823 through I:LM852). The BLMs in circulating beam (I:LM100, etc.), being part of the Main Injector ring, are handled through the MBP microprocessors.

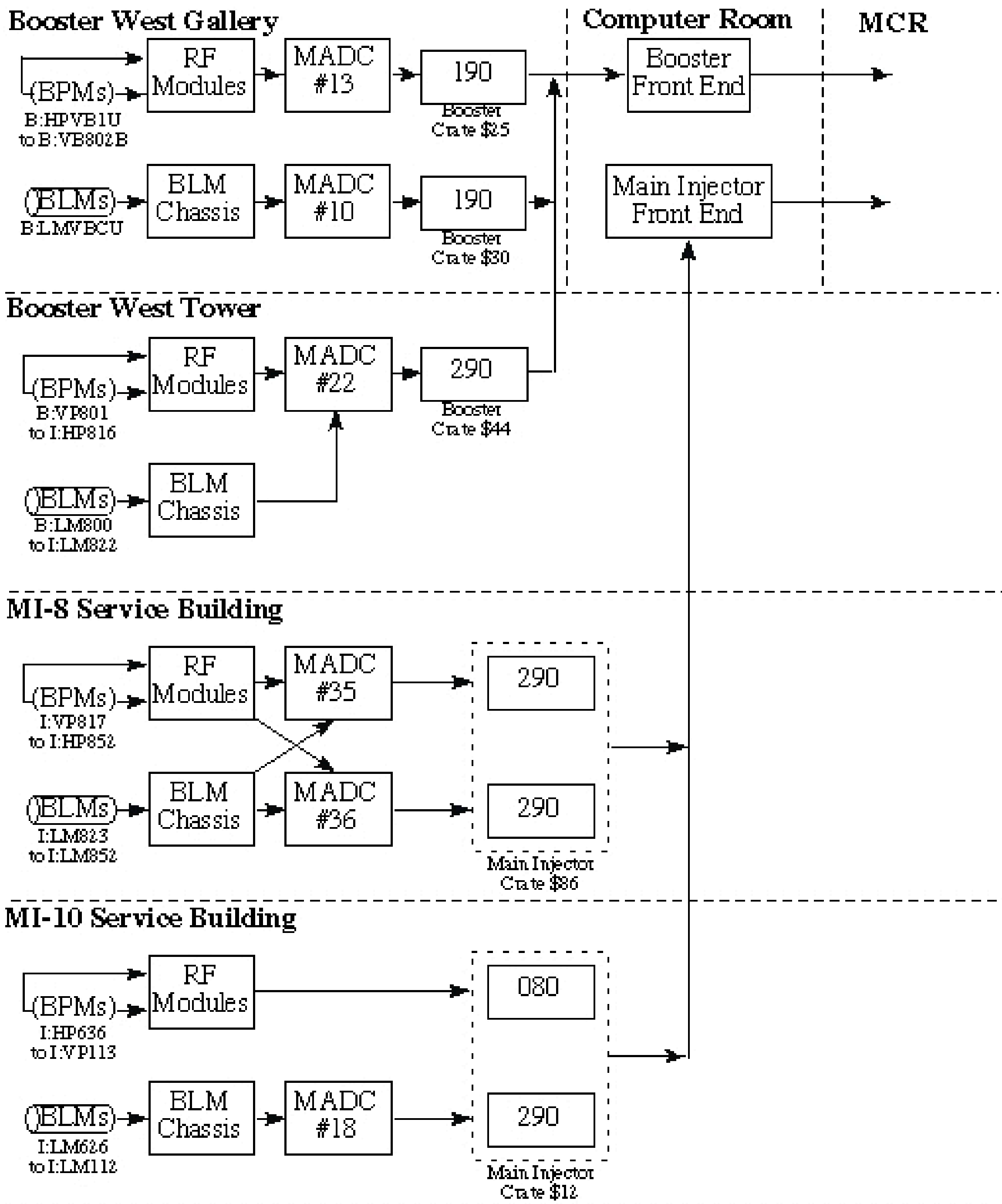


Fig. 7-13 MI-8 BPM and BLM Readbacks

The BPMs, like the BLMs do not use the MBP microprocessors. However, calculations of beam position and intensity are done on board the individual BPM modules and passed on to the MADCs. The ACNET parameter names for the calculated values are HPxxx and VPxxx for the beam positions, and HIxxx and VIxxx for the beam intensities (xxx representing the location). The BPM applications page I39 assembles those readbacks into a coherent picture.

The reason that the MBP microprocessors are not used in the beam line is that there is no need for the averaging of orbit positions for display frames, nor is there a need to collect the multiple snapshot frames necessary for constructing profile buffers. One flash frame is sufficient for a single pass.

The two toroids, TOR800 and TOR852, are obviously located at the endpoints of the line. Readbacks are through the MADCs. The TOR800 electronics is located in the Booster West Gallery, and the TOR852 electronics is at the MI-10 Service Building.

The MI-8 multiwires (Fig. 7-14 located on the next page) are distributed over a large distance, and consequently require the services of several different segments of the controls system.

Multiwires 800 through 830 communicate with the controls system through CAMAC 184 and 192 cards. MW800, 802, and 804 report to Booster Crate $31 in the Booster West Gallery; MW810, 811, 813, and 814 talk to Booster Crate $45 in the Booster West Tower; and MW825, 826, and 830 are connected through Main Injector Crate $86 in the MI-8 Service Building.

Multiwires 836, 839, 840, 851, 101, 102, 103, and 104 are operated through SWIC controllers similar to those found in Switchyard. 836 and 839 are found in the MI-8 Service Building, and the rest are located in the MI-10 Service Building. There is an ARCNET loop at each house that ties the SWIC controllers to the local VME crate, so that the data can be sent back via Ethernet toward the MCR.

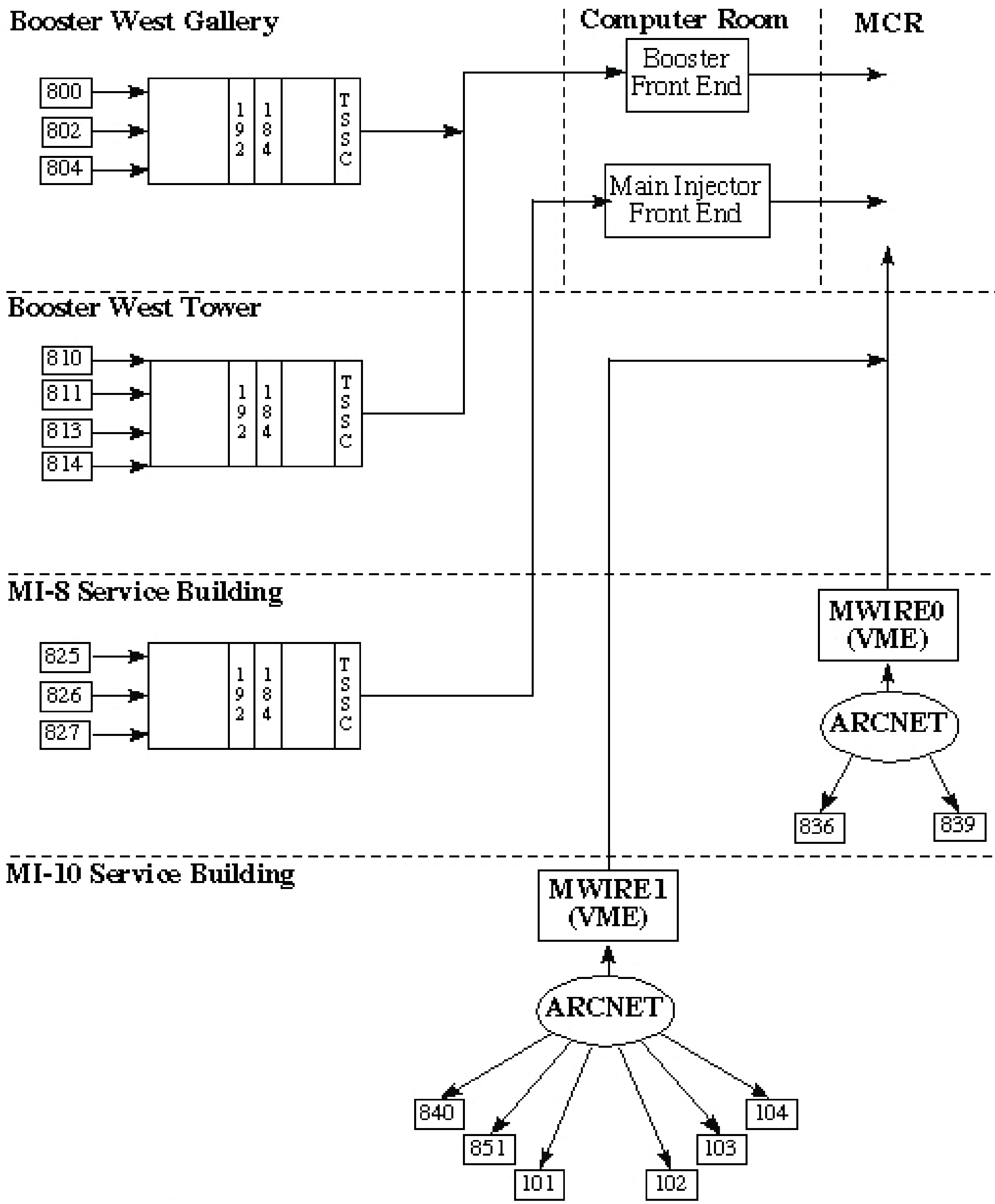


Fig. 7-14 MI-8 Multiwire

Multiwires 101 through 104 must only be used when beam is aborted on the first turn, since they are in the path of circulating beam.

The horizontal Flying Wire and the Ion Profile Monitor are located downstream of Q102; their vertical counterparts are just downstream of Q103. They have been placed in locations where injected beam can be compared to circulating beam. Both of these types of instrumentation are controlled through Mac's. These computers have a built-in Ethernet adapter, so data can be loaded directly onto the local Ethernet hub.

Timing for the MI-8 line diagnostics is coordinated through the Booster Extraction Sync.

The Abort Line

Protons circulating in the Main Injector are normally sent to one of several destinations—the Tevatron, the Fixed Target experiments, the Antiproton Source, or NuMI. Sometimes the beam needs to be disposed of without being sent to a user. This can happen routinely, as during machine studies, or unexpectedly, such as when an abnormal situation is detected. The beam has enough energy to create radioactive isotopes from the metals in the magnets and the beam pipe; in order to minimize residual radiation from aborted beam, the beam is sent to a beam absorber (also known as the beam abort or the abort dump.) The beam still activates the materials in the absorber, but losses are localized and easily isolated.

In the Main Injector (and the Recycler), beam is aborted from the straight section at MI-40 (Fig. 7-15). This section will deal with several aspects of the abort line. There are kickers to deflect the beam horizontally. Lambertsons are needed to bend beam down vertically. There are several dipole and quadrupole magnets in the line to steer the beam and keep it focused on its way to the absorber, and they must be prepared to abort the beam at any energy between 8 GeV and 150 GeV. The magnets and the beam absorber require water-cooling. Finally, some consideration will be given to the set of logical conditions used to determine if the beam will be aborted.

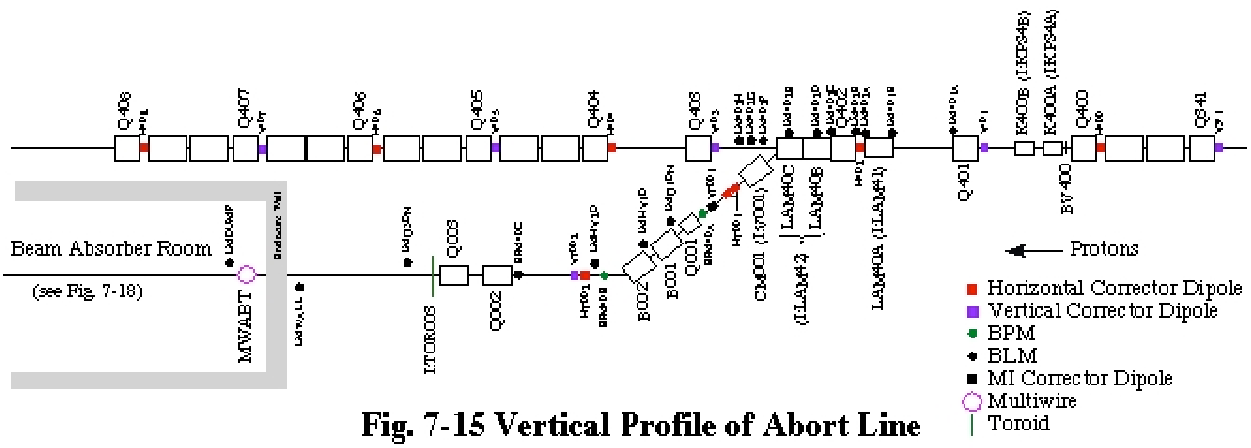


Fig. 7-15 Vertical Profile of Abort Line

Vertically, the beam is pushed down, out of the ring. Horizontally, it is bent to the right. The abort line passes through the enclosure wall and on to the abort dump. The vertical scale of the abort line is exaggerated.

The ACNET names differ from the magnet names and are given in parentheses—they normally indicate controllable power supplies. All of the magnets downstream of I:V001 are powered by the main quadrupole busses and are not individually controllable. B001, B002, and Q002 are powered from the QF bus; Q001 and Q003 are on the AD bus.

Incidentally, antiprotons are not aborted from the Main Injector. They are normally circulating only during Collider mode, and their numbers are not sufficient to justify the expense of a second absorber.

Abort Kickers

The two abort kickers are recycled from the Main Ring, where they served the same purpose. They are located just downstream of Q400, at the beginning of the straight section at MI-40. Background information on kickers can be found earlier in this chapter.

Two conductors flank the elliptical beam pipe inside the kickers. Viewing the magnet from the perspective of an approaching proton, the pulse of current first enters the conductor on the left side of the magnet and returns through the one on the right. For one brief shining moment (about 10 microseconds), the current creates an upward-pointing field in the beam pipe; protons experience a force that pushes them to the right. As with other kickers, the field is intensified by surrounding ferrite.

The charge is stored for the abort kickers in a PFN instead of a PFL. The PFN consists of 14 modules made up of capacitors and inductors. The kicker has to be able to carry the current required to abort the beam for the entire 10 microseconds of the Main Injector revolution (at least during Fixed Target mode). Such a long pulse would require a prohibitive amount of cable for a PFL.

In the kicker room at MI-40, there are three high voltage cabinets for each of the two kickers—one for the PFN, one for the Thyratron, and one for a pulsed transformer that steps down the voltage (for higher current) just before being sent to the kickers. The NIM and CAMAC controls are similar to those of the other kickers (Fig. 7-16).

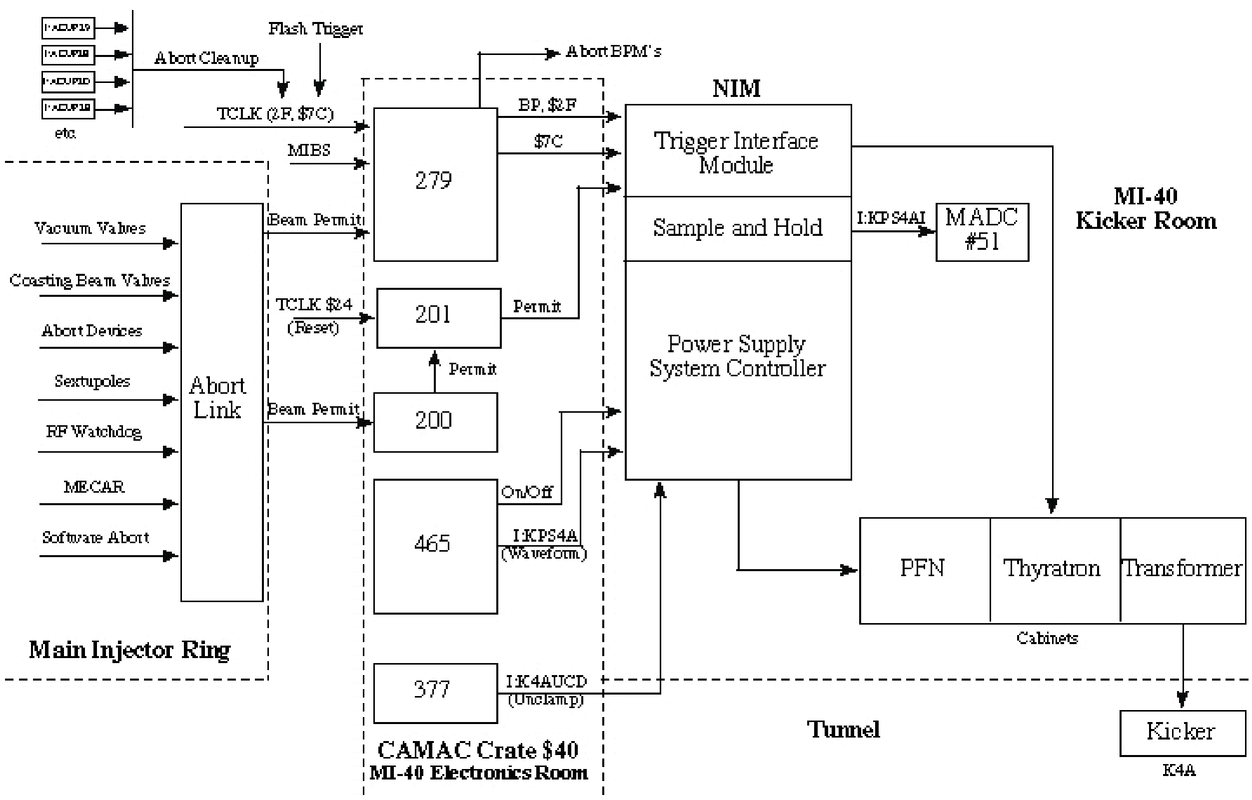


Fig. 7-16 Abort Kicker Control

This diagram shows a few of the permits and timers that control the upstream abort kicker, K4A. A diagram for the second kicker, K4B, would be similar.

The kickers must be able to abort the beam at a moment's notice, at any energy, so the charge stored in the PFN must be matched to the beam energy at all times. The ACNET parameters for the charging waveforms are I:KPS4A and I:KPS4B. The waveforms, played from CAMAC 465 cards, are reset-specific and track the Main Injector program momentum (M30). Digital control is also implemented through the C465. The unclamp parameters, stored in a 377 card, are I:K4AUCD and I:K4BUCD; they are issued with each machine reset.

Each kicker has its own Trigger Interface Module, which in turn gets its timing pulse from a CAMAC 279 beam sync decoder module. (To simplify the following discussion on timing, only Kicker A parameter names will be mentioned. Kicker B uses similar names.)

There are three main inputs into the 279 module: TCLK, MIBS, and the beam permit:

- TCLK encodes the $2F, or abort cleanup pulse. The cleanup pulse is reset dependant and is set for a time in the cycle when the beam is no longer needed. For example, on a $29 cycle the cleanup pulse occurs after the scheduled extraction time to Pbar but before the end of flattop. If for some reason extraction does not happen, the beam is still aborted in a controlled fashion. The $2F itself is generated from a 377 module in the MAC Room; the $2F is a summation of the I:ACUPxx series, where xx stands for a Main Injector reset event.
- MIBS controls the precise time that the kicker begins to fire, which must occur during the gap in the beam. When the 279 card intercepts the $2F from TCLK, it waits for the $AA marker on MIBS and then counts down the correct number of buckets to the gap before sending the timing pulse to the trigger module.
- If the beam permit is removed (i.e. the abort permit is dropped), the trigger is fired. This can happen at any time in the cycle. The cleanup pulse is irrelevant in this case, but the 279 card must still wait for the proper bucket in order to insure that the beam is aborted cleanly. More on the beam permit is on the way.

The $2F and the loss of the beam permit are summed into a single MIBS delay time, I:K4APFD (i.e., if the permit is lost before the cleanup is scheduled, the beam gets aborted anyway).

Another way of aborting the beam is to use the TCLK $7C event. The $7C, or flash trigger, is unusual in that the TCLK event itself is generated by another 279 module, which is in the MAC room. This option is used when aborting the beam on the first or last turn. Since the flash trigger and the abort time are synched to the same source it is possible to get a coordinated picture of a single turn. The delay time between the $7C and the abort trigger is given by the parameter I:K4AKD1.

The choice between I:K4APFD and I:K4AKD1 is made by turning them on or off from a parameter page.

The BPMs in the abort line get their trigger pulse from the same 279 card.

Abort Lambertsons

The "standard" Lambertsons developed for the P1 and A1 lines are also used in the abort line—except that in the abort line, the magnets are connected with the opposite polarity so that the beam is bent down instead of up (Fig. 7-15). There is one Lambertson magnet upstream of Q402 (LAM40A) and two downstream of Q402 (LAM40B and LAM40C).

The rightward kick from the kickers places the aborted beam in the field region, and of course, the circulating beam passes through the field-free notch. It is important that any aborted beam be pushed cleanly over to the field region, but it is perhaps even more important that the circulating beam have a clear path through the Lambertsons (after all, aborted beam is the exception, not the rule). This is achieved partly by offsetting the main horizontal quadrupoles (Q400, Q402, and Q404) to produce a three-bump from the quad steering. Q400 is offset slightly to the left (that is, to the inside of the ring), so that beam sees, on average, a push to the left. Therefore, at the Lambertsons 90˚ in phase space away, circulating beam is further to the left and fits more comfortably in the field-free notch. Q402 is offset to the right, so the beam sees a push to the right. Q404 is offset to the left, completing the 3-bump. The main quadrupoles, of course, roughly track the energy of the beam.

More Magnets

Once beam is clear of the Lambertsons, there are several more magnets for steering beam toward the absorber. The first is a “C” magnet called CM001. The notch in the magnet that surrounds the beam pipe is relatively shallow; beam coming out of the Lambertsons is on a downward slope, so the circulating beam passes through the upper beam pipe while aborted beam enters the magnet. CM001 bends the beam down further. The ACNET parameter for CM001 is called I:V001.

Following the “C” magnet are two B2 magnets, called B002 and B003. They have been recycled from the Main Ring, and have been rotated 40˚ in order to provide both horizontal and vertical bending. Horizontally, the beam is bent to the right; vertically, since the beam is now close to the proper vertical position, it is bent up so that the downward slope is almost cancelled.

There are also several recycled Main Ring dipole correctors used in the abort line. HT001 is actually a doublet just downstream of CM001; VT001 is just upstream of Q001; and HT002 and VT002 are between B002 and Q002.

So much for the bending magnets. For focusing, there are three quadrupoles. Q001, which with its “odd” designation can be recognized as a defocusing magnet, is just after the “C” magnet. It is a 52” recycled quad from the Main Ring. Q002 and Q003 form a doublet further downstream, and are recycled 84” quads.

Power Supplies and Ramps

Block diagrams of power supplies and their associated magnets can be found on Fig. 7-17.

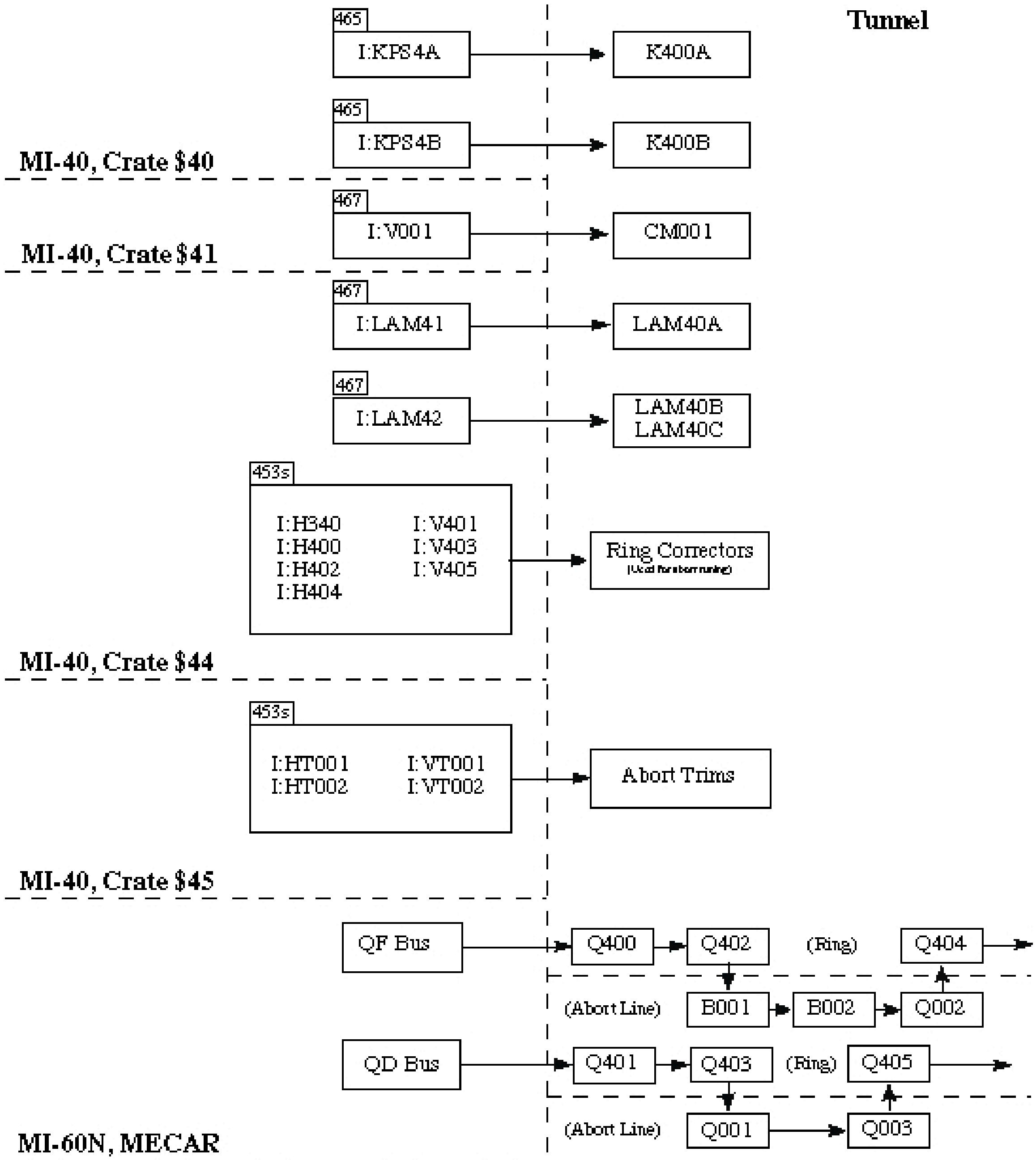


Fig. 7-17 Abort Line Power Supplies
Compare to Fig. 7-15

There are two power supplies for the Lambertsons—I:LAM41 and I:ILAM42. I:LAM41 controls LAM40A, the Lambertson upstream of Q402. I:LAM42 powers LAM40B and LAM40C, which are the two magnets downstream of Q402. As mentioned earlier, I:V001 powers the "C" magnet. The three Lambertsons and V001 form a quartet of downward bending magnets, but they are not always ramped in concert. Since LAM40A lowers the beam going through Q402, quad steering will tend to push the beam back up. This dilemma can be postponed by letting the LAM42 magnets do most of the bending early in the ramp. Then, at higher energies, LAM41 and V001 can be brought into play. LAM41 and V001 are ramped more or less symmetrically so that the angle of descent through LAM42 remains constant. By the time the beam energy is at 150 GeV, all four magnets are sharing the load equally.

Further ahead in this chapter (Fig. 22(a, b, and c)) there are diagrams of beam as it passes through the P1 line Lambertsons. They might be useful for visualizing what is happening in the abort Lambertsons, but remember that beam is being pushed down in the abort line, and up in the P1 line.

The Lambertsons and "C" magnet are controlled through CAMAC 467 cards in Crate $41.

Several magnets are powered through the main quad busses, and therefore have no ACNET parameters or independent control. B001, B002, and Q002 are on the QF bus, while Q001 and Q003 are powered from the QD bus.

The Absorber Room

The beam pipe of the abort line, which has been deflected downward and to the right from the Main Injector ring, passes through the enclosure wall near 406. Eventually it enters the Absorber Room (Fig. 7-18).

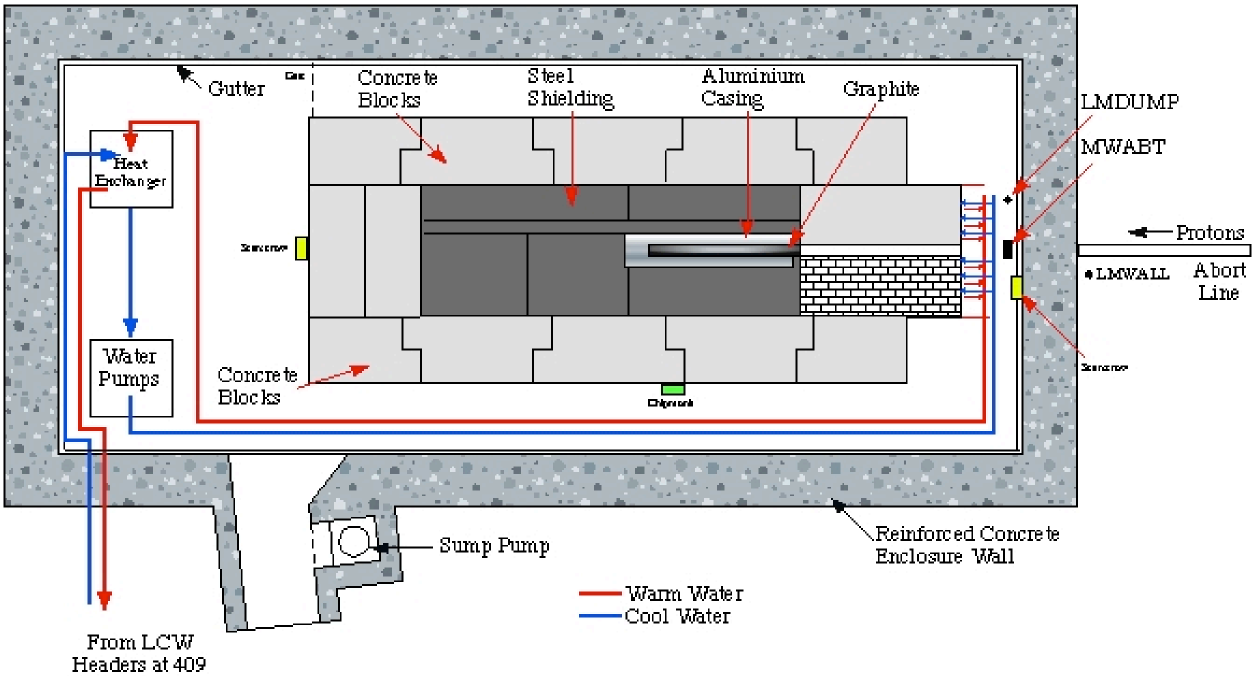


Fig. 7-18 Beam Absorber Room (Top View)
The aborted beam, arriving from the right, is stopped by a series of materials. First is the graphite core, which absorbs much of the thermal energy and slows the secondary neutrons as well. The graphite is contained in an aluminum sheath that is surrounded by steel and then concrete.

The steel, which conducts heat readily, contains numerous channels for water cooling. The closed loop system prevents activated water from entering the main lines. Compare Fig. 4-3 and 7-15.

The purpose of the absorber is to shield the outside world from exposure to the high-energy beam, which creates radioactive isotopes in the materials it encounters. It consists of several concentric layers.

Graphite: Graphite, similar to that found in pencil “lead,” is a form of pure carbon (although in pencils, the graphite is mixed with clay to make it harder). Unlike the chemically identical diamond, in which the carbon atoms are polymerized in three dimensions, the carbon atoms in graphite are only polymerized in two dimensions; graphite is therefore much softer than diamond.

Why graphite? One reason is its high temperature of sublimation (it doesn't melt) — about 3825˚C. During periods of tune-up in the Main Injector, the absorber may be required to take a thousand or more hits an hour of 120 GeV beam, which represents a significant thermal load.

The other major reason for using graphite is its ability to slow down energetic neutrons. Fast neutrons produced when the protons hit the target collide with the relatively light carbon nuclei and lose much of their energy; otherwise, they might penetrate the walls of the absorber room. "Fast" neutrons are converted to "thermal" neutrons.

And, of course, graphite is cheaper than diamond.

The graphite absorber is shaped as a long cylinder. The beam impacts the cylinder along its longitudinal axis and is therefore attenuated by several meters of graphite. The graphite is encased in an aluminum sheath.

Steel: The second line of defense against secondary particles is the steel surrounding the graphite core. Steel is a relatively inexpensive, yet relatively dense material that can stop many secondary particles.

Embedded in the steel are numerous water channels for carrying off the heat radiating from the graphite. The outer dimensions of the steel block, looking head-on, are 2' by 2'. The water system is described in more detail below.

Concrete: Finally, the graphite/steel block is surrounded by large concrete blocks. The blocks are a cheap way of providing a lot of additional shielding.

Water Cooling: (Background information on LCW systems in general can be found in Chapter 4.) As mentioned above, channels used for water-cooling permeate the steel block. The water, although heat exchanged with the LCW from the main headers, is a closed loop system. This is because the water itself can be activated by energetic secondary particles passing through the steel. There are short-lived isotopes that can decay in a matter of minutes, but there is also tritium (H^3), with a half-life of over 12 years.

A simplified drawing of the abort water system is included with Fig. 7-18. Three inch supply and return headers branch off from the main LCW headers at 409 (which is also the location of the stairwell entrance to the absorber room). The LCW makes a single pass through a small heat exchanger and returns to the main header. Flow is maintained by the differential pressure between the supply and return headers.

Within the closed loop system, warm water returns from the channels in the absorber, passes through the secondary loop of the exchanger, and is cooled by the LCW. Circulation is maintained by two small pumps.

A 21-gallon storage tank receives the makeup flow from the LCW supply line. As is usually the case, head pressure on the tank is maintained with nitrogen gas. Makeup water from the storage tank to the abort system enters the return line just upstream of the pumps. Also, a "recirculation" pump siphons excess water from the high-pressure side of the abort system and transfers it to the tank.

The configuration of the abort cooling system is somewhat simpler than most of the other water systems in the Main Injector because there is no need to deionize the water (it doesn't pass through any electrical components), nor is there a need to precisely control the temperature of the absorber—it just needs to be kept reasonably cool.

Abort Link

The beam permit is based on the abort link, which originates in a CAMAC 201 module in the MI-40 electronics room. The signal launched from the 201 module is repeated from building to building by the CAMAC 200 abort concentrator modules. The purpose of the concentrator modules is to accept local inputs that are able to interrupt the signal and break the link, which causes the abort kickers to fire. Refer to the Controls Rookie Book for more details on abort links in general.

Compared to the Tevatron, the Main Injector 200 modules are sparsely populated with inputs. All of the inputs can be found on I67. At all houses, a closing vacuum valve will pull down the permit—there is no sense in pounding a valve with beam. In addition, at MI-30 there are two beam valves (BV301 and BV309) specifically designated to stop beam in the unlikely event that all else fails—these are also tied in to the abort. At MI-40, the inputs are from the power supplies for the abort line itself—for the kickers, Lambertsons, and C-magnets. At MI-52 the inputs come from the vertical and horizontal sextupoles, at MI-60S it is the RF watchdog (that also inhibits the anode supply); and at MI-60N it is MECAR that pulls the abort if the main power supplies are becoming too much of a problem.

Finally, at MI-10 there is the ever-mysterious "Software Abort." Through this input, any ACNET parameter can become an input to the abort system with the proper modifications to the database; many of the loss monitors in the abort line itself can pull the abort. Of course, in a case like this, the abort is already in progress and its real purpose is to inhibit the next pulse of beam, and to make operators aware of the problem.

When an abort is reset, TCLK event $24 is broadcast on the clock. When the C201 module intercepts the $24, it attempts to restart the abort link.

TCLK event $27, issued by the BSSB, is an announcement to hardware that "Beam has been aborted." By creating a time stamp, the $27 creates a record of the exact time of the abort that can be useful in diagnosis.

The P1, P2, and P3 lines each have their own permit systems, to be described in the next sections. Since there is no way—or need—to abort beam from these single-pass lines, the permit system can only prevent unwanted beam from entering those lines.

Abort Diagnostics

Beam diagnostics for the abort line include a multiwire (MWABT), a toroid (TOR003), and a dense array of loss monitors. TOR003 is upstream of the absorber room, and MWABT is located just inside the wall where the beam pipe enters the absorber room. There are also BPMs, but they are seldom if ever used. Fig. 7-19 shows the abort system located in the MI-40 service building.

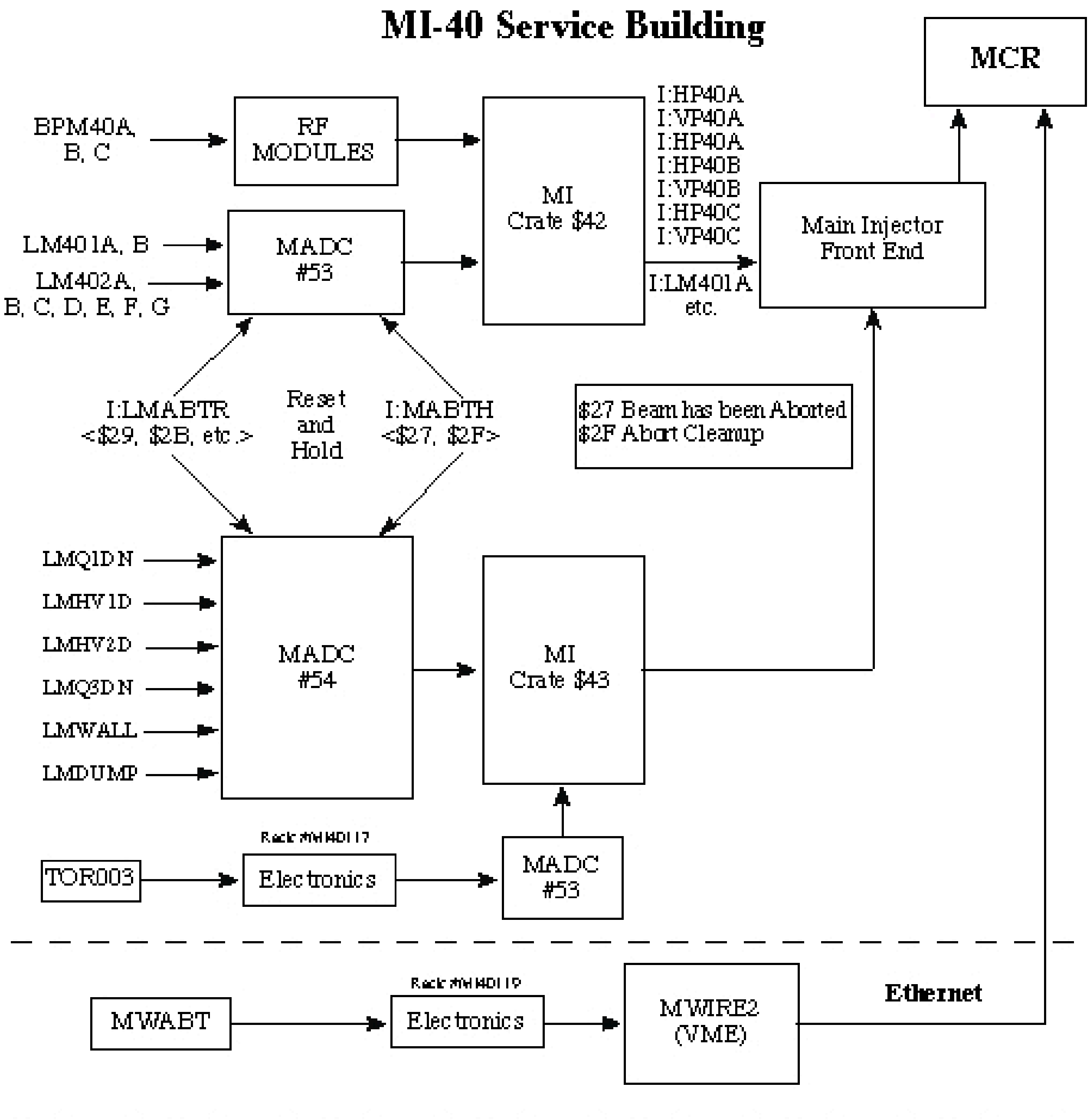
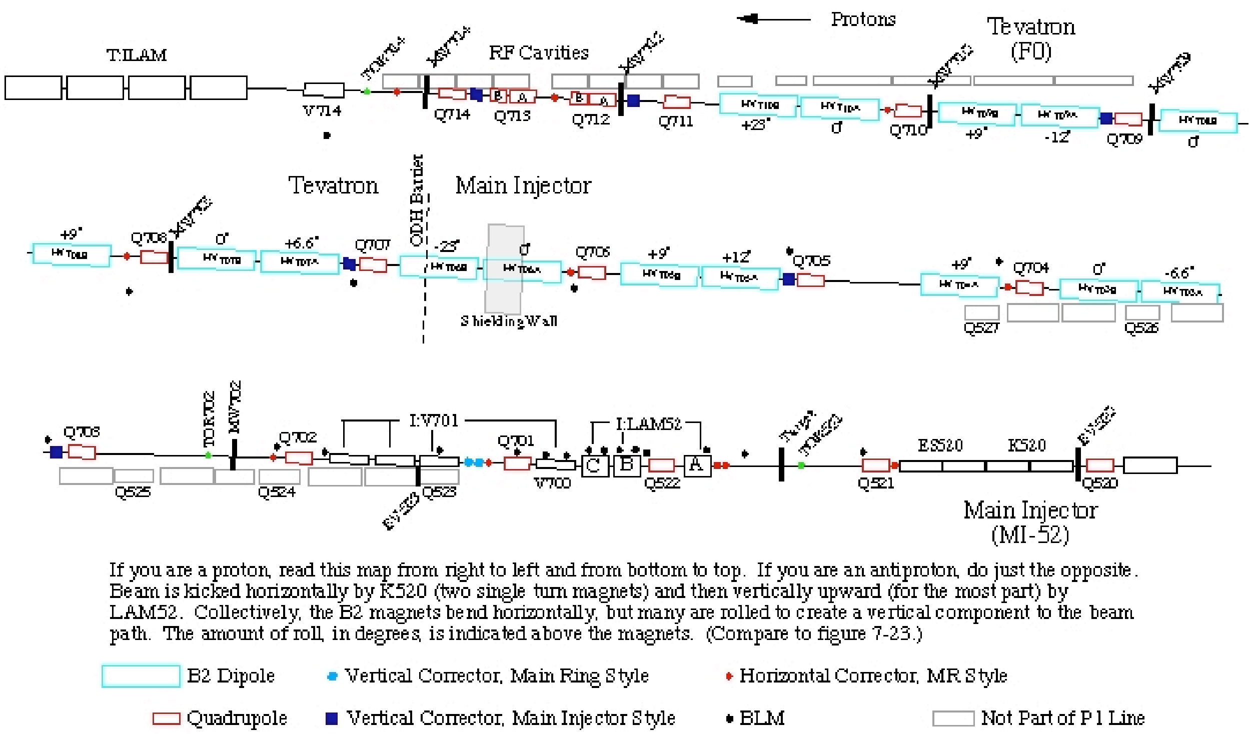


Fig. 7-19 Abort Diagnostics

I:LMABTR, the abort reset trigger, is referenced to the Main Injector machine resets ($29, $2B, etc.) with a delay of about half a millisecond. I:LMABTH is the "hold" event that tells the BLMs to latch onto the integrated value; it is referenced to $27 and $2F events with a delay of 5 milliseconds (enough time for the loss monitors to integrate the charge). The latched values can be read on a parameter page, but, in practice, real-time plots of critical monitors (such as I:LMQ3DN) are used while tuning.

The P1 Line

The P1 line connects the Main Injector to the F0 Lambertsons (Fig. 7-20). It is used by protons extracted from the Main Injector and by antiprotons entering the Main Injector. Operationally, it is probably the most complex of all the beam lines, because it must transport beam in both directions and at several different energies. It also sends protons toward two distinct destinations—the Tevatron and the P2 line—each of which requires customized beam trajectories and optics (Figs. 1-4, 1-5, 1-6, 1-8, and 1-9). In addition, the Main Injector, Tevatron, and P2 line are all at different elevations.



If you are a proton, read this map from right to left and from bottom to top. If you are an antiproton, do just the opposite. Beam is kicked horizontally by K520 (two single turn magnets) and then vertically upward (for the most part) by LAM52. Collectively, the B2 magnets bend horizontally, but many are rolled to create a vertical component to the beam path. The amount of roll, in degrees, is indicated above the magnets. (Compare to figure 7-23.)

Fig. 7-20 Vertical Profile of the P1 Line

In this book, the beginning of the P1 line is considered to be at 520, where kickers initiate the extraction process. The end point of the line is the Injection Lambertson at F0 (ILAM), where the beam must choose whether to enter the Tevatron or the P2 line. P1 line locations are designated by numbers in an "I:700" series (not to be confused with numbers in the AP-2 line, which are in a D:700 series).

There are nearly a dozen different operations that use the P1 line to transfer beam from one machine to another. Extracted beam may be headed for the Tevatron at 150 GeV. 120 GeV protons in the line may be used for stacking, or resonantly extracted to Switchyard. The P1 line also sends 8 GeV protons to the Antiproton Source for tune-up; those can be sent to either the Debuncher or the Accumulator.

In the other direction, the line carries 8 GeV antiprotons from the source to the Main Injector, to be accelerated there or deposited in the Recycler. It will also accept 150 GeV antiprotons freshly decelerated in the Tevatron, sending them to the Main Injector to be further decelerated to 8 GeV and stored in the Recycler.

To complicate things further, most of the power supplies used by the P1 line are also shared with the A1 line, because the two lines are, for the most part, symmetrical.

All of these demands on the design of the P1 line can sometimes create complications for the tuner. The approach in this book will be to first describe the line in a general way, and then to go back and discuss the specific adaptations required by different modes of operation.

Several of the beam lines (P1, A1, the abort line and NuMI) are very similar to each other in the way the components are set up in the lattice to extract beam. To minimize redundancy, some of the details will be discussed in excruciating detail for the P1 line so they can be dealt with less harshly in the other sections.

P1 Line Overview

The basic pattern of kickers, Lambertsons, and C-magnets used to extract beam from the Main Injector at MI-52 is similar to that of the abort line, except that beam is deflected up instead of down (Figs. 7-15, 7-20). Vertically, the beam needs to be moved up to the level of the Tevatron, which is 2.133 meters higher, by the time it reaches F0. T:ILAM, if powered, straightens out the upwardly rising beam so that it continues into the Tevatron. If those Lambertsons are not powered, beam continues upward into the P2 line.

Considering the horizontal component, be aware that if the beam were simply allowed to escape at a tangent to the Main Injector at 520, it would quickly reach the Tevatron upstream of ILAM without any assistance from kickers or magnets. Although the kickers kick to the outside of the Main Injector ring, the P1 magnets as a whole continue to bend beam to the left until it is tangent to the circle of the Tevatron at F0.

A majority of the magnets in the P1 line are "rolled" so that they provide both horizontal and vertical changes to the beam trajectory.

The MI-52 extraction kickers are located at the beginning of the straight section, immediately downstream of Q520. There are two single-turn magnets; they kick the beam to the right, toward the outside of the ring. The parameter for the kicker power supply is I:KPS5S, for "Kicker Power Supply at MI-52, Short." The "Short" designation is a historical remnant from the days when there was a "Long" kicker as well. "Short" means up to 84 bunches, or a complete Booster batch, in length. (The kickers are immediately followed by the extraction septa, which are only used during resonant extraction. Except for the origin of the deflection, resonantly extracted beam follows the same path through the P1 line as kicked beam.)

The kicked beam soon finds itself in the field region of I:LAM52, the extraction Lambertsons (Fig. 7-2, 7-22 a, b, & c). There are three Lambertson magnets—LAM52A, LAM52B, and LAM52C, with LAM52A being upstream of Q522, and LAM52B and LAM52C downstream of Q522. Collectively, they begin to bend the beam up toward the Tevatron. The Lambertsons are rolled by 10˚ or so, which helps with the horizontal angle as well. Fig. 2-8(a) shows the short straight-section lattice at MI-52 that must accommodate the extraction devices.

Following the Lambertsons, there are four C-magnets that, on average, deflect the beam down—they are powered in series by I:V701. The first, called V700, is upstream of the first quad in the line (Q701), and the other three, known collectively as V701, are downstream of Q701.
V700 is only used during 120 GeV or 150 GeV extraction and the magnet bends the beam up. By the time the beam reaches Q701, it has risen above the Main Injector centerline by 21.8 cm and has an upward deflection of 28.5 mrad. The magnets of V701, which are powered for all extracted beam, push down on the beam and reduce the upward angle. (A bit more on the reason for this is on the way.)

The large bending magnets in the P1 line are recycled B2 dipoles from the Ring formerly known as Main. One of these, H703B, is independently powered, by I:H703. The task of H703B is to adjust the horizontal angle of the beam. The remaining 14 are powered in series from a common power supply (I:HV703). Walking past the line leaves the impression that an earthquake has recently struck, because many of the magnets have been rolled to produce both horizontal and vertical components to the field (Fig. 7-20 shows the roll angles for the B2 dipoles, in degrees).

Four of the dipoles are not rolled; i.e. they bend the beam only in the horizontal plane. Whether rolled or not, all of the magnets in the I:HV703 series bend beam to the left, bringing it parallel to the Tevatron beam pipe.

The remaining ten of the B2 dipoles each have at least some vertical component to their bending strength. They can be grouped into four "families." The dipoles in the first family are rolled counterclockwise by 9˚. (The convention here is that a counterclockwise roll, viewed from upstream to downstream, is positive, and that the vertical component of the force pushes the beam up.) There are two pairs in this family, and they are responsible for much of the remaining upward deflection in the line.

The remaining three families include one pair of magnets each, with the roll of one in the opposite direction of the other: +/-6.6˚, +/-12˚, and +/-23˚. These rolls are designed to cancel out the vertical dispersion in the line.

At the end of the line, a C-magnet called V714 gives the beam a final push upward to ensure that it will enter the field region of the Lambertsons. V714 pushes even harder if beam is meant to go on up to the P2 line. When all is said and done, there is an upward angle of 24 mrad as the beam arrives at the injection Lambertsons. If the Lambertsons are powered at the time, they cancel the angle, and horizontally level beam continues into the Tevatron. (The beam still has a horizontal angle that must be removed by the F17 kicker in the Tevatron.) If they are not powered, the beam continues to rise toward the P2 line, which is 64.6 cm higher than the Tevatron. In that case, the horizontal and vertical injection angles are eventually cancelled in the P2 line (next section).

In a manner similar to the MI-8 line, the lattice in the middle of the P1 line is flanked on either side with a matching lattice to the adjacent machines. Upstream, of course, is the match to the Main Injector. Downstream, the lattice has to match that of either the Tevatron or the P2 line, which are not identical. The string of quadrupoles from Q703 to Q709 establishes the central FODO lattice in the P1 line; they are powered in series by I:Q703 (Fig. 7-23). Q701 and Q702, which are independently powered, match the P1 FODO lattice to that of the Main Injector. The last five quads, Q710 through Q714, are all individually powered and match the P1 FODO lattice to either the Tevatron or the P2 line. The matching lattice is changed from pulse to pulse by varying the current in the magnets— in particular, the ramp waveforms of Q713 and Q714 change the most.

Of course, there are corrector dipoles in the line, usually located downstream of the appropriate quad. All of the horizontal dipoles are recycled from the Main Ring, while most of the vertical dipoles are of the newer Main Injector style. The vertical correction at 701, however, uses a doublet of MR-style dipoles (VT701-1 and VT701-2). LEP magnets are not used in the P1 line because their high inductances make for a sluggish response to the constantly changing energy requirements.

Now for the excruciating details....

Kickers

As mentioned earlier, there are two kicker magnets downstream of Q520. The pulse is generated by KPS5S, located at MI-52. The pulse has a short flattop and is used to kick single batches or partial batches. It uses a pulse forming line (PFL); that is a long cable, to store its charge. The charge is fed to the cable from a Glassman high voltage supply.

Like the abort line, the P1 line uses TCLK, MIBS, and reflection events for controlling transfers. The biggest difference is that the P1 line has so many of them. Table 7-1, located at the very end of this chapter, attempts to summarize these. The kickers, magnets, and beam diagnostics use the events, plus delays, as triggers. For example, the flash frame delay triggers the BPMs so that they sample the beam at the instant it passes through the line, using many of the same events that allowed the kickers to fire. Every mode of operation has its own unique and complicated set of timers.

As usual, a TCLK event initiates the events associated with charging the supply (Fig. 7-21). For example, during stacking a single batch is injected and accelerated on the $29 cycle. Event $80, the “Stacking Reset” trigger, is actually issued by the TLG one 15 Hz tick (67 ms) earlier than the $29. Devices specifically needed for stacking, such as the kickers and the P1 line magnets, will be referenced directly or indirectly to the $80 event. First, there is the unclamp delay (I:K5SUCD) which, once initiated by the $80, tells KPS5S to begin charging its PFL.

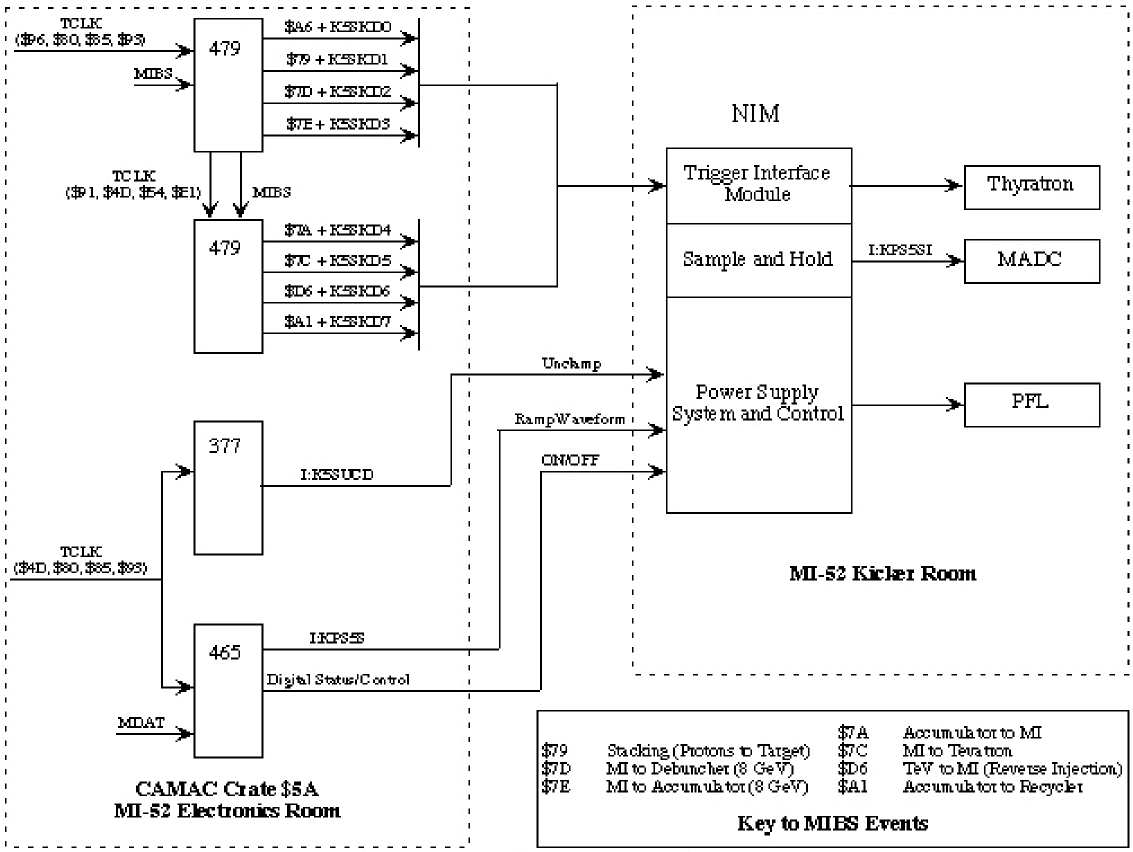


Fig. 7-21 MI-52 Kicker Timing

KPS5S also begins to charge up when it sees events $4D, $85 and $93 (Fig. 7-21, Table 7-1). The $85 and $93 events will transfer 8 GeV beam to the Debuncher and Accumulator, respectively; beam on the $80 event will be at 120 GeV, and the $4D beam will be at 150 GeV. The kickers will charge to a level appropriate for the beam energy. The ramp tables for the kicker waveforms track the MDAT signal for Main Injector momentum.

Once the PFL is fully charged, another trigger is needed to fire the kicker—that is, to unload all of that stored energy into the kicker magnets. Continuing with the story of the stacking pulse, on board a CAMAC 377 card in Slot 3, Crate $94 (home of MIBS) there is a timer called I:MIPBTX. This timer, with a value (as of this writing) of .905555 seconds, initiates the extraction of beam. It begins counting down the interval as soon as it decodes an Event $80 from TCLK.

When the time is up—and it had better coincide with flattop on the $29 cycle—the 377 issues a pulse which, after some processing by other cards in Crate $94, is transformed into the beam sync Event $79 and broadcast on MIBS. Event $79 is, in turn, decoded by a 479 card in Crate $5A at MI-52. The 479 card now knows that it must choose a moment in the very near future to send the timing pulse to the Trigger Interface Module; that moment must be just as the leading edge of the batch approaches the kickers, taking into account the rise time of the kickers.

Once armed, the 479 card begins its own countdown. The countdown delay, set from the parameter I:K5SKD1, is given as 24.9 "MREV," or "Main Injector Revolutions." (It is actually counting in "RF buckets," in groups of seven, with one revolution equal to 588 buckets.) Since the bucket offset between the location of the batch and Event $79 is fixed, the delay can be set so that the kicker fires at the correct bucket.

The parameters for the kicker delay times are listed in Table 7-1.

Mode of Operation	TCLK	Beam Sync	BS Reflection	BS Delay	Flash Delay	Ext Kicker	Inj Kicker	Beam Lines
Booster to Main Injector	$2x	BES			I:BPFTBM	MKS02	MI10	MI-8
Tevatron Fixed Target	$4D	$78	$58	I:MITPX	I:BPFTBM	MI52	F17K	P1
TeV Collider, Forward Protons	$4D	$7C	$5C	I:MITCPX	I:BPFT7C	MI62	F17K	P1
Main Injector to TeV Antiprotons	$40	$7B	$5B	I:MITPBX	I:BPFT7B	MI62	E48	A1
TeV to MI Antiprotons	$34	$D6	$5F	I:MITBX	I:BPFTD6	F17K	MI52	P1
Reverse Protons, TeV to MI	$5D	$D8	$55	I:TMIPX	I:BPFTTM	E48	MI62	A1
STACKING	$80	$79	$81	I:MIPBTX	I:BPFTMD	MI52	D:IKIK	P1, P2, AP1, AP2
MI Protons to Debuncher	$85	$7D	$86	I:MIDX		MI52	D:IKIK	P1, P2
Accumulator to MI Antiprotons	$91	$7A	$94	I:AMIPBX	I:BPFTAM	D:EKIK	MI52	A3, AP1, P2. P1
Reverse Protons to Accumulator	$93	$7E	$99	I:MIAX	I:BPFT7E	MI52	D:EKIK	P1, P3
Recycler to Accumulator Protons	$96	$A6	$97	R:RAX		RR30	D:EKIK	RR30, P1, P2, AP1, AP3
Accumulator to Recycler Antiprotons	$E1	$A1	$98	R:ARX		D:EKIK	RR30	AP3, AP1, P2, P1, RR30
Main Injector to Recycler Protons	$E2	$A2	$F2	R:MIRPX	I:BPFTA2			RR20
Recycler to MI Protons	$E3	$A3	$F3	R:RMIPX	I:BPFTA3			RR30
Recycler to MI Antiprotons	$E4	$A7	$F7	R:RMIPBX	R:BPxAFD			RR20
MI to Switchyard	$30	$75	$39	I:MIBLX	None	Septa	None	P1, P2, P3
MI to NuMI	$A5	$74	$A9	I:MINX				NuMI

Table 7-1 Beam Line Timing

The tables for the kicker waveforms are stored in a CAMAC 465 card in Crate $5B in the MI-52 Service Building. The C377 and C479 cards for the unclamp and trigger signals are located in the same crate.

Lambertsons and C-Magnets

The extraction Lambertsons (I:LAM52) and the C-magnets (I:V701) differ from the other magnets in the P1 line in two ways: (1) Their power supplies are not shared with magnets in the A1 line, and (2) Different subsets of each magnet string are powered, depending on the energy of the extracted beam. 8 GeV beam calls for one set of magnets, while 120 or 150 GeV calls for another. When a change from one configuration to another is required, the ramp waveform goes to zero current, and “load transfer switches” connect the proper magnets to the power supplies. The switch defaults to the 120/150 GeV state.

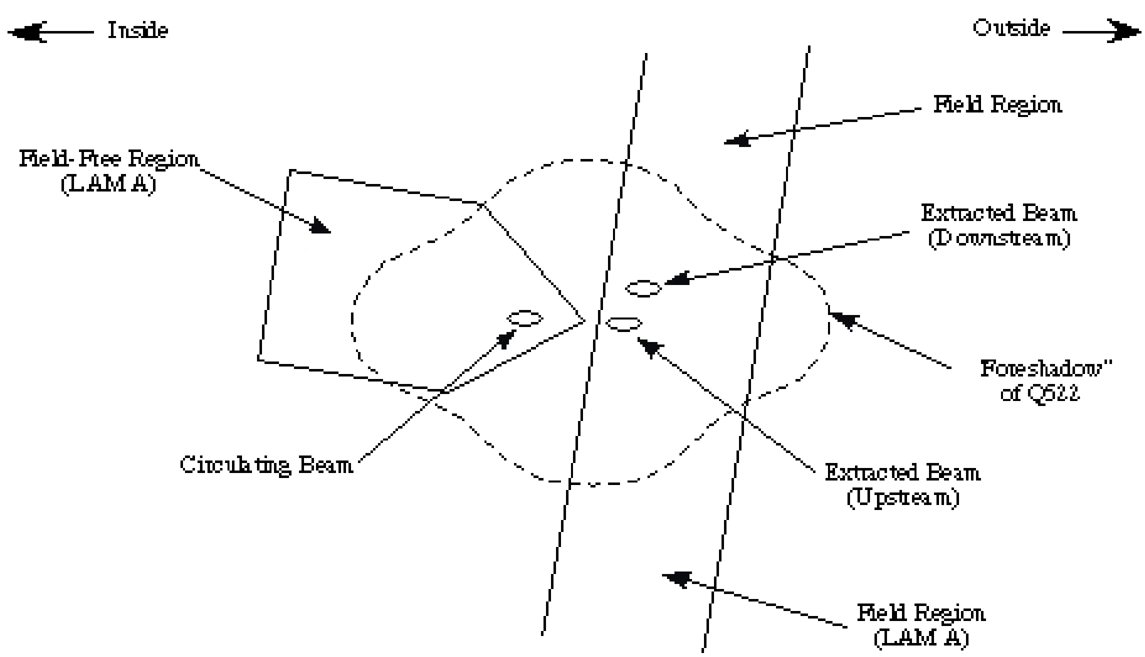


Fig. 7-22(a) 150 GeV Beam at LAM A

The extraction kickers at 520 deflect the beam into the field region of LAM A, which in turn bends it up and slightly outward

In the case of the Lambertsons, remember that there are actually three magnets—LAM52A, LAM52B, and LAM52C. During 120 or 150 GeV extraction, all three are powered. But during 8 GeV extraction, only LAM52B and LAM52C are powered. Why is this switch necessary? Let me tell you. At 120 or 150 GeV, the strength of three Lambertsons is required to give the beam enough of a deflection to clear the beam pipe by the time it reaches Q701. In fact, there is an additional C-magnet, V700, which is used to help push the beam up even further. But there is only enough room for two Lambertsons (B and C) between Q522 and Q523. The remaining Lambertson (A) is located upstream of Q522 (Figs. 7-20, 7-22(a) and (b)).

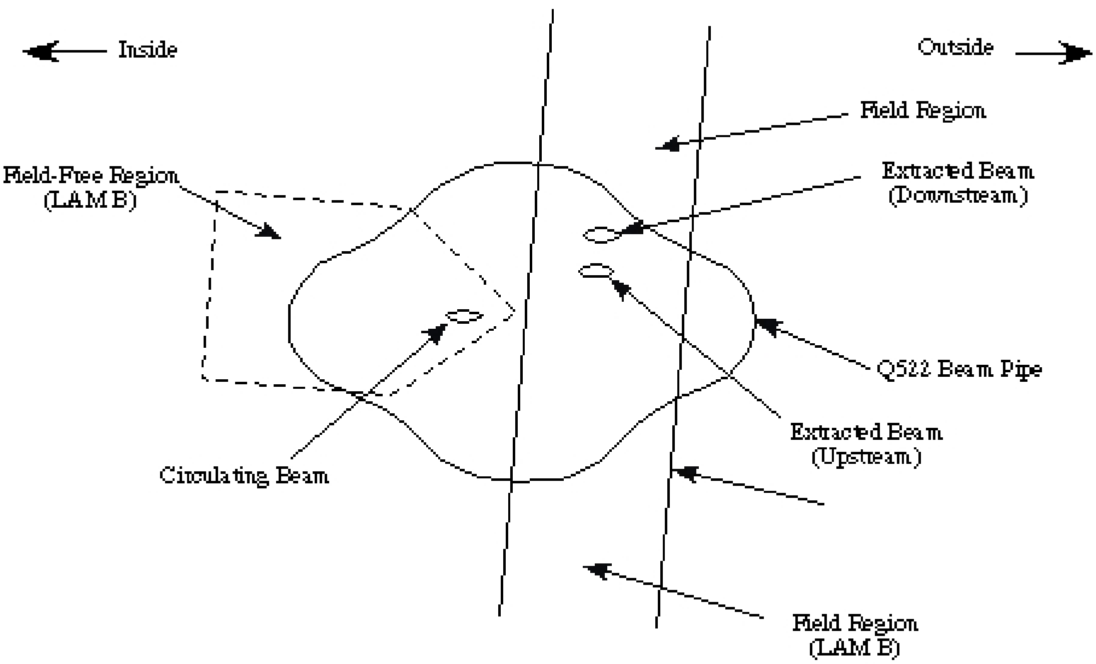


Fig. 7-22(b) 150 GeV Beam at Q522

At Q522, the extracted beam continues to move on its upward trajectory, and is helped slightly by the vertically defocusing field of the quadrupole. Compare to Fig. 7-20.

8 GeV beam, however, is not only easier to deflect, it is also bigger (Fig. 7-22(c)). In order to go cleanly through the field region at LAM52, the beam is kicked horizontally and steered to the outside. That means that beam will also be to the outside as it enters Q522, which is just downstream of LAM52. If 8 GeV beam were to be bent vertically up at LAM52A, as 150 GeV beam is, it would scrape on the upper surface of the beam pipe at Q522. So, at 8 GeV, LAM52A and V700 are disconnected from their respective power supplies.

When an 8 GeV clock event is detected, the ramp current goes to zero, the Load Transfer Switch removes LAM52A from the circuit, and current is sent only to LAM52B and LAM52C. Near the end of the 8 GeV cycle, current again goes to zero, the switch adds LAM52A to the circuit, and all three Lambertsons are set up to ramp on the following cycle if needed.

In the case of I:V701, remember that the first C-magnet, V700, is distinct from the following three C-magnets because it bends the beam up rather than down. V700 behaves like LAM52A—during 120 or 150 GeV extraction, all four magnets are powered; with an 8 GeV event, the ramp goes to zero, V700 is removed from the circuit, and the remaining three are powered.

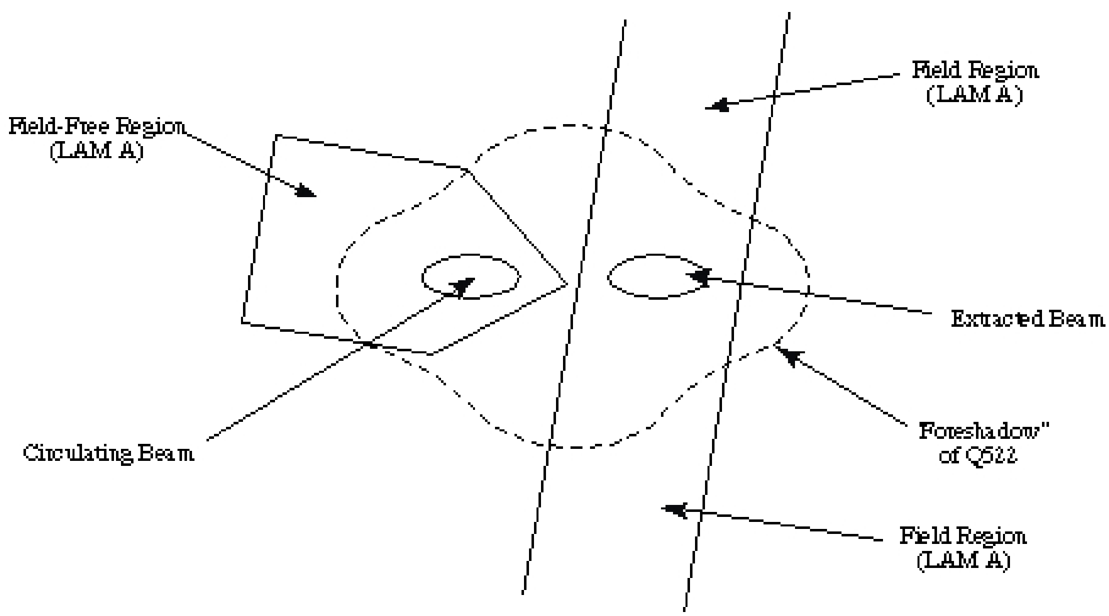


Fig. 7-22(c) 8 GeV Beam at LAM A, P1 Line

LAM A stays off so that extracted beam does not scrape on the beam pipe at Q522

At 8 GeV, if LAMA were to be turned on, the large and easily swayed beam would scrape the top of the beam pipe. The extraction Lambertsons are in series for all 120 or 150 GeV extraction. However, when beam is to be extracted at 8 GeV, as during a $2D cycle, I:LAM52 is ramped down to zero amps and a transfer switch LAMA out of the circuit (Fig. 7-23). Then, since the beam remains vertically centered through Q522, LAMB and LAMC can be ramped up to their 8 GeV value.

V700 is disconnected from the I:V701 supply at the same time as LAMA is disconnected from I:LAM52.

The load transfer switches are triggered by the parameter I:LS8ON, which itself is referenced to 8 GeV reset events ($93, $85, $E1, etc.). When I:LSSON is active, the 8 GeV subset of magnets is connected. I:LS8OFF, referenced to the same events but with a longer delay, turns the switches off, and connects the magnets needed for 120/150 GeV operation. The switch from 8 GeV to 120/150 GeV is sometimes referred to as "S1," to distinguish it from the switch "S2" that transfers power between the P1 line and A1 line magnets (to be discussed later).

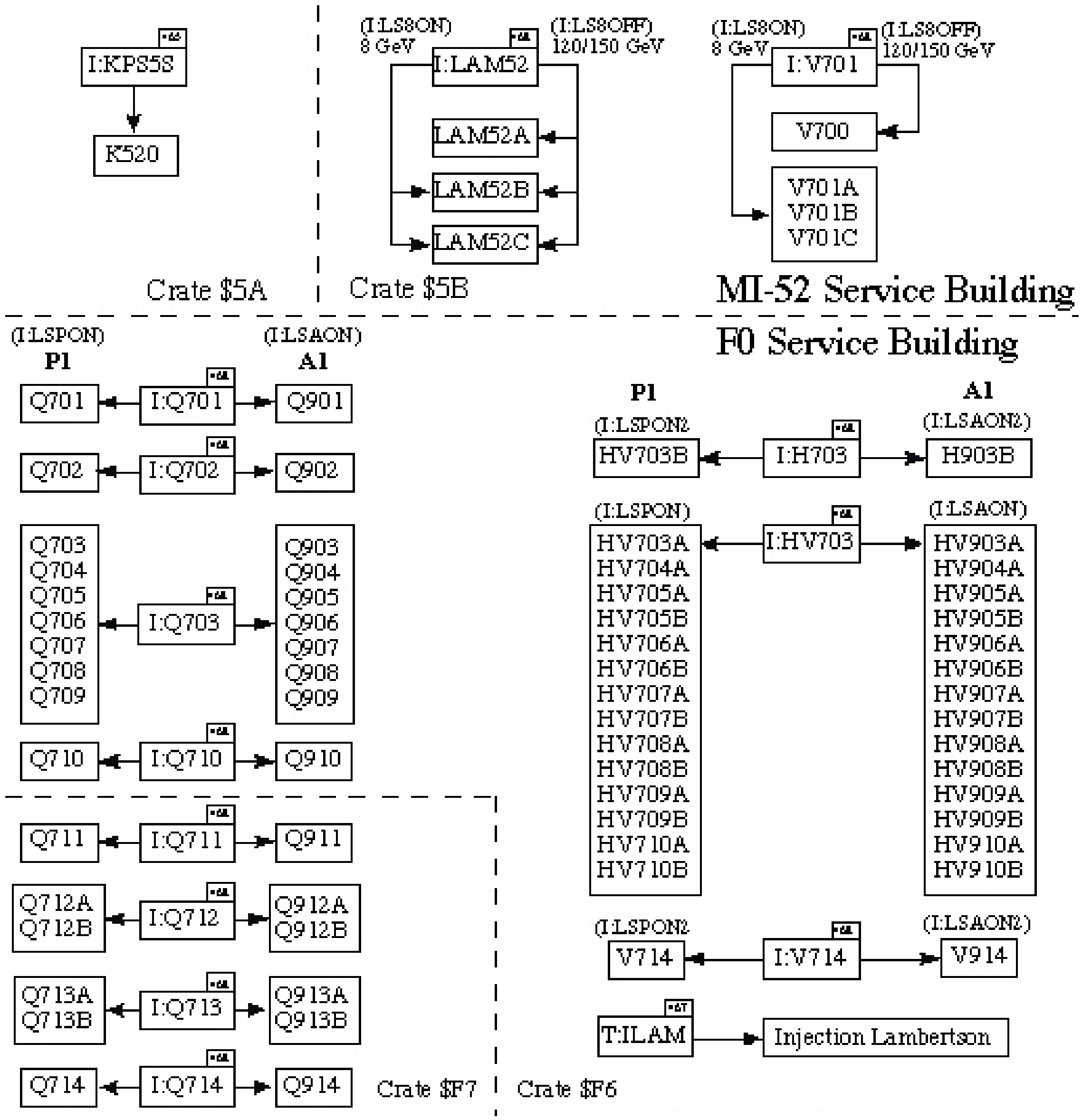
The ramps for I:LAM52 and I:V701 are stored in CAMAC 468 cards located in Crate $5B at the MI-52 Service Building. A 377 card in the same crate generates I:LS8ON and I:LS8OFF. The 468 ramps used by the 8 GeV events are set up to go to zero current at those times when the load transfer switches are potentially active.

The Rest of the Magnets

The power supplies for the rest of the magnets are found at the north end of the F0 Service Building. As mentioned earlier, H703, Q701, Q702, Q710, Q711, Q712, Q713, and Q714 are independently powered and controlled, whereas I:HV703 and I:Q703 power many magnets in series (Fig. 7-23). Their ramp tables are stored in 468 cards, but from a practical standpoint they are controlled from the applications page I68. Making seemingly innocent modifications (such as for the current values during extraction) actually requires changes at several levels of the ramp to assure continuity from cycle to cycle; I68 calculates these changes automatically.

The P1 (and A1) corrector power supplies are merely regulators that share the Corrector Power Supplies for the ring magnets (Fig. 7-29). The upstream trims, VT701 to VT709, use CPS6S, and those downstream use CPS6N.

A second load transfer switch, S2, allows the power supplies to switch back and forth between the P1 and A1 line supplies; I:LAM52 and I:V701 are exempt because the equivalent devices in the A1 line only need to run at 150 GeV.



Most of the major power supplies in the P1 line lead a double life for one reason of another; the modes are changes via load transfer switches. At the beginning of the line, I:LAM52 and I:V701 are disconnected and reconnected to certain magnets, depending on the beam energy. Most of the remaining elements in the line must periodically share power supplies with corresponding magnets in the A1 line. I:Q703 is on when beam is to be injected into the Tevatron, and off when beam is destined for the P2 line.

The timer parameters (in parenthesis) tell the transfer switcher when to connect to the indicated magnets.

Fig. 7-23 P1 Line Power Supplies

Beam Diagnostics

P1 line diagnostics (Fig. 7-24) include BPMs, BLMs, multiwires, and toroids.

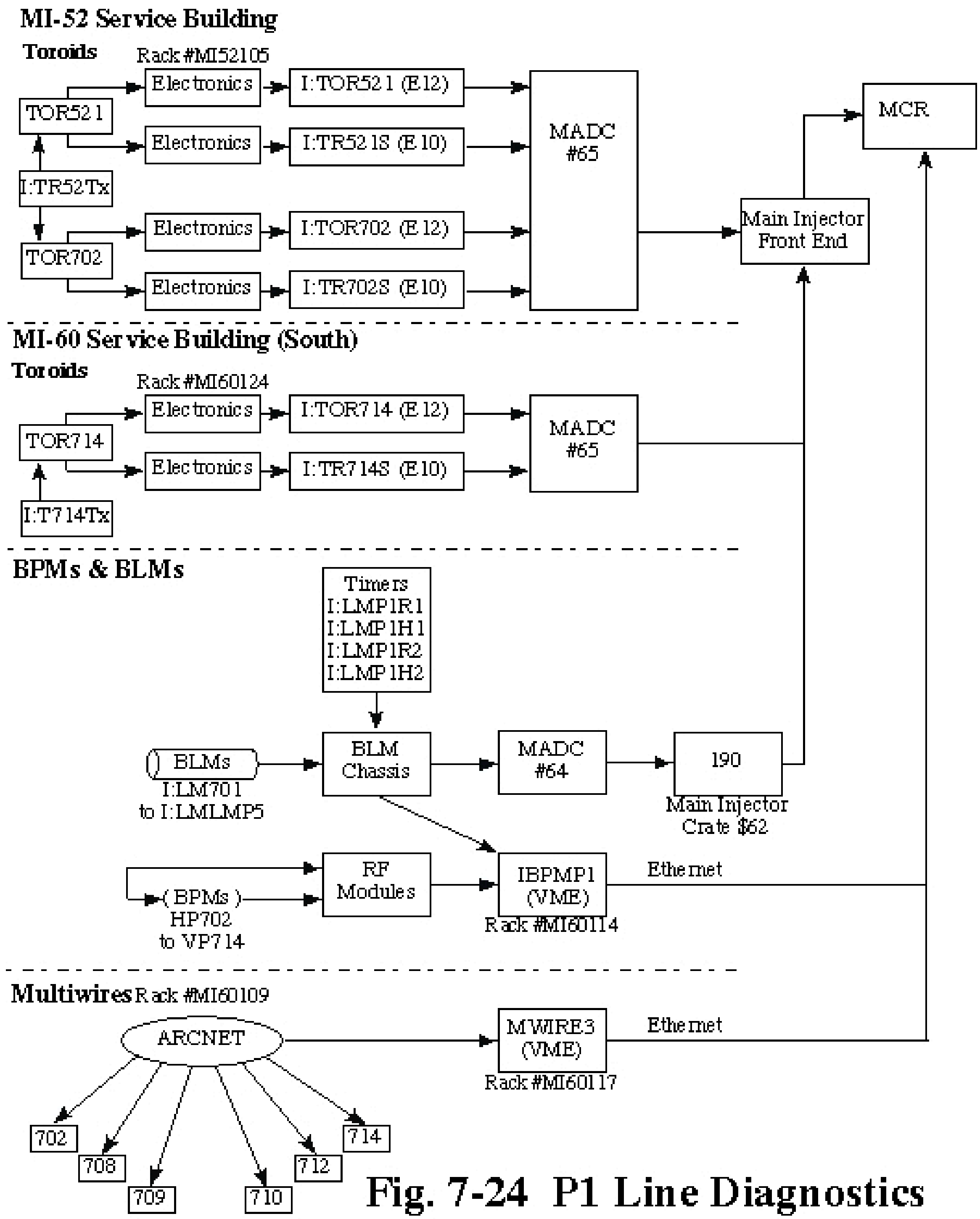


Fig. 7-24 P1 Line Diagnostics

Being a single-pass line, the only BPM option on I39 is the flash frame; choosing the cycle to display is a matter of choosing the proper beam sync trigger. Each beam sync clock event has a flash delay associated with it; the delays are all stored in 279 cards in Switchyard Crate $09 in the MAC room.

The delays can be found on I39 and are listed in Table 7-1 (the last of the pictures at the end of this chapter). I39 can be used to view the P2, P3, and A1 lines as well.

The "Timing" window on I39 offers several options for setting the flash frame delay times:

(1) BPTRIGS opens a window that includes most of the beam sync events and flash delays associated with beam transfer to and from the Main Injector. For example, if looking at reverse proton tune-up to the Accumulator, I:BPFT7E—the Beam Position Flash Trigger for MIBS 7E—would be enabled.

All of the events in the BPTRIGS series are ORed together. Enabling an event and launching an SA will display a continuous update of positions in the beam lines. If more than one extraction event is selected, however, the events will overwrite each other. Since the selections are not console-dependant, altercations in the control room may develop as one person's data obliterates another's.

(2) BP1EXx, the P1 BPM beam sync triggers are designed to prevent this conflict. They are triggered independently of BPTRIGS:

I:BP1EXT ($7D, $7E)
I:BP1EX1 ($7C)
I:BP1EX2 ($79)
I:BP1EX3 ($78)

Time delays in MREV can be chosen by the user. This option allows studiers—or automated programs—to collect flash data on particular events without interfering with the BPTRIGS frames.

(3) BPDELAY encompasses the parameters I:BPFTD1 and I:BPFTD2, which are user-controlled delays that can time the flash frame with respect to any TCLK event (as opposed to a beam sync event). In practice, BPDELAY is used more for diagnosing problems with circulating beam than it is for the beam lines.

BPMs in the P1 line interface with the controls system through IBPMP1, a VME crate at MI-60 south. The node can be rebooted through the parameter I:VRST61.

There are about two-dozen loss monitors in the P1 line. I:LM701 through I:LM714 are located near the quads Q701 through Q714, respectively. The density of BLMs is highest at the upstream and downstream ends of the line: at V701 (LMPC1U, LMPC1M, and LMPCD) and V714 (LMPC2U, LMPC2M, and LMPC2D—the “C1” and “C2” designations come from the fact that V701 and V714 are C-magnets). In addition, the Tevatron Injection Lambertson is instrumented with I:LMLMP1 through LMLMP5 (“Loss monitor” and “Lambertson” use the same abbreviation in these parameter names.)

The window of integration for the loss monitors in the P1 line is currently 5 milliseconds. The timing does not have to be incredibly precise; the only requirements are that the window be open when the beam passes through the line, and that the interval is short enough to prevent noise and background radiation from overwhelming the signal. The trigger and hold times are referenced to the TCLK events or reflections of the beam sync event (e.g. $80, $86, $5C, $94, $99). The reflection event appears only when the associated beam sync event is issued and a beam transfer is expected.

The reset time is set by I:LMP1R1 or I:LMP1R2; the hold time is set by I:LMP1H1 or I:LMPH2.

There are six multiwires in the P1 line: MW702, MW708, MW709, MW710, MW712, and MW714. They are controlled from page I41. The wires are controlled through a card in the MWIRE3 VME, located in the electronics racks at MI60S.

Main Injector

Since Main Injector acceleration cycles that use the P1 line come in many different varieties, the usual “Start, Sample, Stop” clock events are inadequate to set the timing for the multiwires. Instead, a 377 card at MI60S has been co-opted for that role. Fortunately, each cycle only uses the P1 line once, so each 377 timer can be assigned a delay referenced to the appropriate clock events. These timers can be found in the “External Events” box, to be enabled or disabled as needed.

The two toroids in the P1 line are TOR702 and TOR714. TOR521, which measures circulating beam at the point of extraction, can also be useful. Obviously, a comparison of the three is a measure of P1 line transmission efficiency.

Beam in the P1 line can be high intensity, such as during stacking, or low intensity, as during Pbar transfers. Therefore, the raw signal from each toroid is sent to two amplifiers: low gain amplifiers for I:TOR521, I:TOR702, and I:TOR714 that produce traces calibrated in units of E12, and high gain amplifiers for I:TR521S, I:TR702S, and I:TR714S, calibrated in units of E10 (the "S" stands for "small").

The triggers for TOR521 and TOR702 are based on I:TR52Tx, where x is 0-7; each value of x represents a TCLK event. (Like the BLMs, toroids can get away with the less precise timing of TCLK because all they need is an integration window that includes the beam pulse. The TCLK event is usually a beam sync reflection.) The series I:T714Tx triggers TOR714. Times for TOR714 are set about 23 microseconds later than the others, accounting not only for the time of flight of the beam down the line, but also for propagation delays of the TCLK events from the MAC room.

The parameter page I34 lists many timers related to beam diagnostics, including those for the toroids; most toroid timers can be found in the “8 GeV” sub pages.

LCW

Most of the magnets in the P1 line–-beginning with the C-magnets—are cooled by the stand-alone LCW system at the MI-52 Service Building. The setup is similar in many respects to a "regular" service building, details of which can be found in Chapter 4. Exceptions to the norm are discussed below; be sure to consult the graphics on page I56.

The system includes a storage tank; head pressure on the tank ultimately determines the pressure in the return line (V02 must remain open in order for the pressure to be transmitted). Water can be added to the system from the makeup tank by opening V03 and turning on the small makeup pump S06. Makeup water is also obtainable from the Main Injector system. Makeup water is added, as always, to the return side.

The supply pressure at MI-52, about 250 PSI, is higher than that in the rest of the ring.

The pond pumps are located a significant distance from MI-52, behind the MI-50 Service Building.

Vacuum

Vacuum is maintained with ion pumps. BV701 isolates the P1 line from the Main Injector. BV714 and BVF11 isolate the TeV Injection Lambertson.

P1 Line Permits

I:LAM52 and I:V701 are critical devices for F Sector and the Pre-Target Enclosure, as well as being the failure mode (backup) devices for the Tevatron CDC, in the unlikely event that T:ILAM should fail to trip off. There are also radiation monitors that will trip the critical devices. The critical device parameter name is I:P1INJ.

There is also a P1 line permit system, analogous to an abort system but only designed to inhibit beam. It is completely distinct from both the safety system and the Main Injector abort. All of the major power supplies for the P1 line magnets, as well as BV701, are tied in to it. When the permit is removed, the BSSB will instruct the Linac pulse shifter not to accelerate beam if it is destined to pass through the P1 line on its way to the Tevatron, Pbar, or Switchyard.

The P2 Line

The P2 line is the section of the Main Ring remnant that begins at the Injection Lambertson (ILAM) and ends with the B3 dipole at F17 (Fig. 7-25).

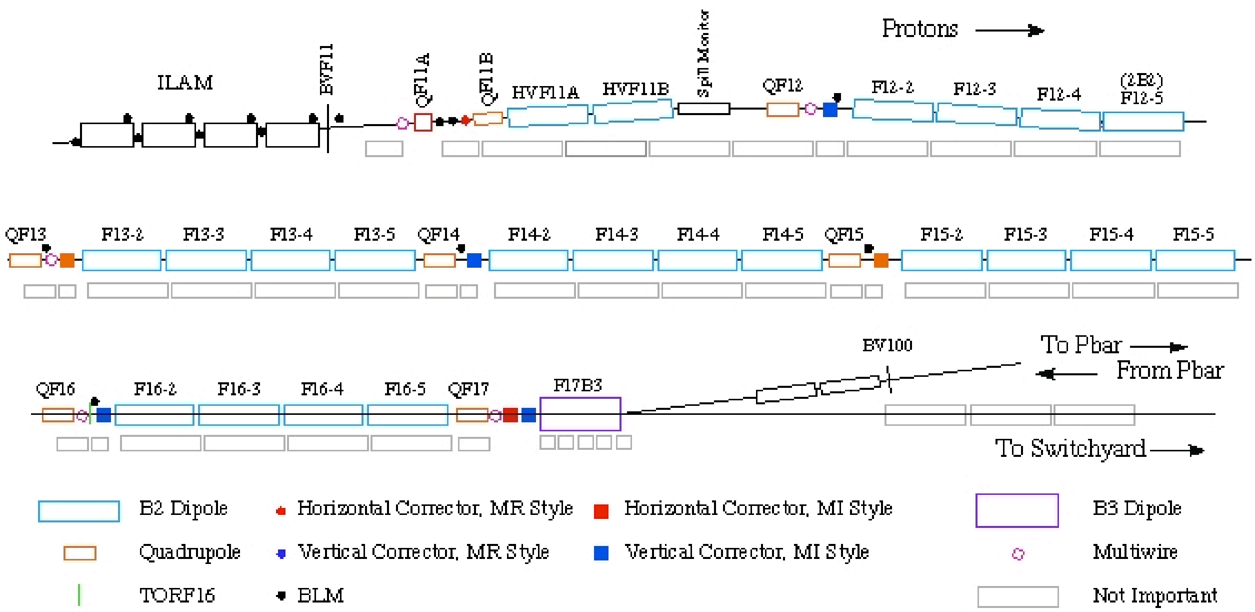


Fig. 7-25 Vertical Profile of the P2 Line

The P2 Line connects the P1 Line to F17B3 (compare to fig. 7-20, 7-26). If T:ILAM is not pulsed, the beam continues to rise until it reaches the two magnets at F11 (powered by HVF11). Those two magnets are skewed to provide a downward vertical deflection that cancels the upward angle of the beam. Skewed B2 dipoles at F12 then deflect the beam down to the level of the old Main Ring and finally remove the downward vertical angle. From QF13 to F17B3, the beam essentially traces part of a circle through the old Main Ring.

If F17B3 is powered, beam will be bent up into the AP-1 Line. If not, beam continues into the P3 Line.

The P2 Line can run at either 8 GeV or 120 GeV. At 8 GeV, it is probably being used for reverse protons, or for antiprotons arriving from the Accumulator. At 120 GeV, protons are being sent to the Pbar target or to the Fixed Target experiments.

It is used by 120 GeV protons headed toward the Pbar target, 8 GeV antiprotons from the Accumulator headed toward the Main Injector, or 8 GeV protons headed for the Antiproton Source for tune-up purposes (Figs. 1-4, 1-5, and 1-9). In the future, it will also be a bridge for 120 GeV beam to the P3 line and the Fixed Target experiments (Fig. 1-6).

The numbering/naming system has been inherited from the Main Ring, where the seven main quadrupoles defined the locations F11-1 through F17-1. (Unlike the Main Injector, the Main Ring had no consistent convention assigning even and odd numbers to focusing and defocusing quads. In fact, from F12 through F17, it turns out to be just the opposite.) Then there were four dipoles following each quad—for example, F14-2, F14-3, F14-4, and F14-5 followed F14-1. The quads have been renamed (e.g. F14-1 is now QF14), but most of the dipoles stay the same.

The original Main Ring lattice from F13-1 through F17-1 has remained (more or less) intact. The region through F11 and F12 has been reworked extensively to match the lattice and geometry of the P1 line.

Remember from the last section that beam in the P1 line is moving upward as it approaches ILAM. Then, if ILAM is pulsed, the beam is deflected downward so that it is horizontal, and it continues into the Tevatron. If ILAM is not pulsed, beam continues upward into the P2 line.

Most of the P2 line is 64.6 cm (25”) above the Tevatron, as inherited from the Main Ring. However, the geometry coming out of the P1 line is such that beam overshoots slightly. The first task of the P2 line is to bend the beam down until it is at the correct level. The B2 dipoles HVF11A and HVF11B, both powered by I:HVF11, straighten the beam to the horizontal, although it is still too high. The four dipoles at F12 then act as a dogleg to bend the beam down and straighten it horizontally at the correct level.

The dipoles at F11 and F12 are, for the most part, rotated. This is because the Main Ring was, of course, a ring, and the beam has to conform to the horizontal curvature even as it is bent vertically.

The last dipole in the F12 string is a double-strength B2 dipole (called a B2B); it serves to complete the vertical dogleg as well as provide bending for the horizontal curvature.

There are two major quadrupoles upstream of the HV11 dipoles—QF11A and QF11B. They are individually controllable.

The region from F13 to F17-1 is nothing more than the original Main Ring lattice, serving here to transport beam to and from F17. This is a FODO lattice much like that of the Main Injector, except that there are four dipoles for every quadrupole instead of two. There are five 84" quads between F12 and F17B3. The dipoles, from the Main Ring, are of the "B2" style. (Unlike the original Main Ring lattice, that used both B1 and B2 dipoles, all of the dipoles in the P2 line are the magnets with the larger vertical aperture.)

There is a "cradle" attached to each main quadrupole that can hold correction elements. In the P2 line, the original dipole correctors have been replaced by Main Injector style dipoles, except at F11. (As with the P1 line, LEP dipoles lack the agility required to track the ramps used in the P2 line.) The higher-order correctors such as the sextupoles, octupoles, and skew quads have been removed because this is a single-pass line.

At the end of the line is F17B3, a B3 dipole from the Main Ring. If the magnet is not powered, beam sails on into the P3 line and presumably on to Switchyard. F17B3 lies on its "side" and is primarily a vertical bend; it deflects protons into the AP-1 line. 8 GeV antiprotons approaching from the AP-1 line, such as during a shot, are bent onto the proper path in the P2 line. The magnet is therefore powered to either an 8 GeV or 120 GeV level.

Power Supplies

Magnets near the beginning of the P2 line, where tuning is the most critical, tend to have individual power supplies (Fig. 7-26). Further, down the line there is a tendency to clump them all together. QF11A and QF11B each have a dedicated supply (I:QF11A and I:QF11B); HV11A and HV11B are both powered by I:HV11. All of the remaining main dipoles are powered from I:HVF12, and all of the remaining quads from I:QF12.

I:QF11A and I:QF11B are 75 KW Spang supplies located at the north end of F0. I:HVF11, and I:QF12 (which must power six quads in series), are 500 KW PEI supplies, also found at the north end of F0. The latter two supplies produce enough power to require their own dump circuitry.

Power Supplies	Cards	Magnets	Location
I:QF11A (75KW Spang)	468	QF11A	F0 North
I:QF11B (75KW Spang)	468	QF11B	
I:HVF11 (75KW Spang)	468	HVF11A HVF11B	Main Injector Crate $F7
I:QF12 (500KW P=E1)	468	QF12 (F12-1) QF15 (F15-1) QF13 (F13-1) QF16 (F16-1) QF14 (F14-1) QF17 (F17-1)	
I:HVF12 (Main Ring P.S.)	A468	F12-2 F13-2 F14-2 F15-2 F16-2 F12-3 F13-3 F14-3 F15-3 F16-3 F12-4 F13-4 F14-4 F15-4 F16-4 F12-5 F13-5 F14-5 F15-5 F16-5	F1 Service Building Main Injector Crate $1F
I:CPSF1	453s	I:VTF11 I:VTF14 I:HTF11 I:HTF15 I:VTF12 I:VTF15 I:HTF13 I:HTF17 I:VTF17	Main Injector Crate $5F
I:F17B3 (Main Ring P.S.)	468	F17B3	F2 Service Building Tevatron Crate $F6

Fig. 7-26 P2 Line Power Supplies
Compare to Fig 7-25

I:HVF12, which must power many large dipoles in series, is a modified Main Ring power supply located in the F1 service building.

The dipole corrector supplies, I:VTF11 through I:VTF17, are powered from I:CPSF1 and controlled from three 453 cards.

The supply for F17B3 is located in the F2 service building. I:F17B3, like I:HVF12, is a modified Main Ring supply.

LCW

The Tevatron LCW pump and the pond pumps at F1 are responsible for cooling the magnets in the P2 line and the I:HVF12 power supply. The cooling is shared with the TeV HOPS and corrector power supplies.

Vacuum

The P2 line can be isolated from the upstream world by BVF11, which is just downstream of ILAM (Fig. 7-25). BV100 can be closed to isolate the AP-1 line (indeed, this valve is sometimes inadvertently left closed after accesses). Although F17B3 is considered the end of the P2 line, the vacuum sector actually extends through F19; a third valve at F19 isolates the P2 line from the P3 line (not shown on Fig. 7-25).

The vacuum system for the P2 line has been inherited directly from the Main Ring; in fact, parameter names begin with M: instead of I:.

A roughing pump and a diffusion pump are connected to a pump down line at F15. The roughing pump is upstairs, between the motor control center breakers and the air compressor; the diffusion pump is downstairs at F15. (The concept of a diffusion pump has not yet been introduced in this book—basically, it heats and vaporizes oil; the hot droplets absorb air molecules and carry them away from the beam pipe. The diffusion pump does its work over approximately the same pressure range as a turbo molecular pump.)

Finally, there are ion pumps between each magnet; the supplies for the ion pumps are upstairs at the F2 Service Building. An LED on the front of each supply indicates whether the supply is on or off. Vacuum is monitored by thermocouple (TC) gauges. A CAMAC 145 card in the electronics room is the interface to the controls system.

More detail on the vacuum system can be found in the old Main Ring Rookie Book.

Beam Diagnostics

Beam diagnostics for the P2 line, and their controls links, are shown in Fig. 7-27.

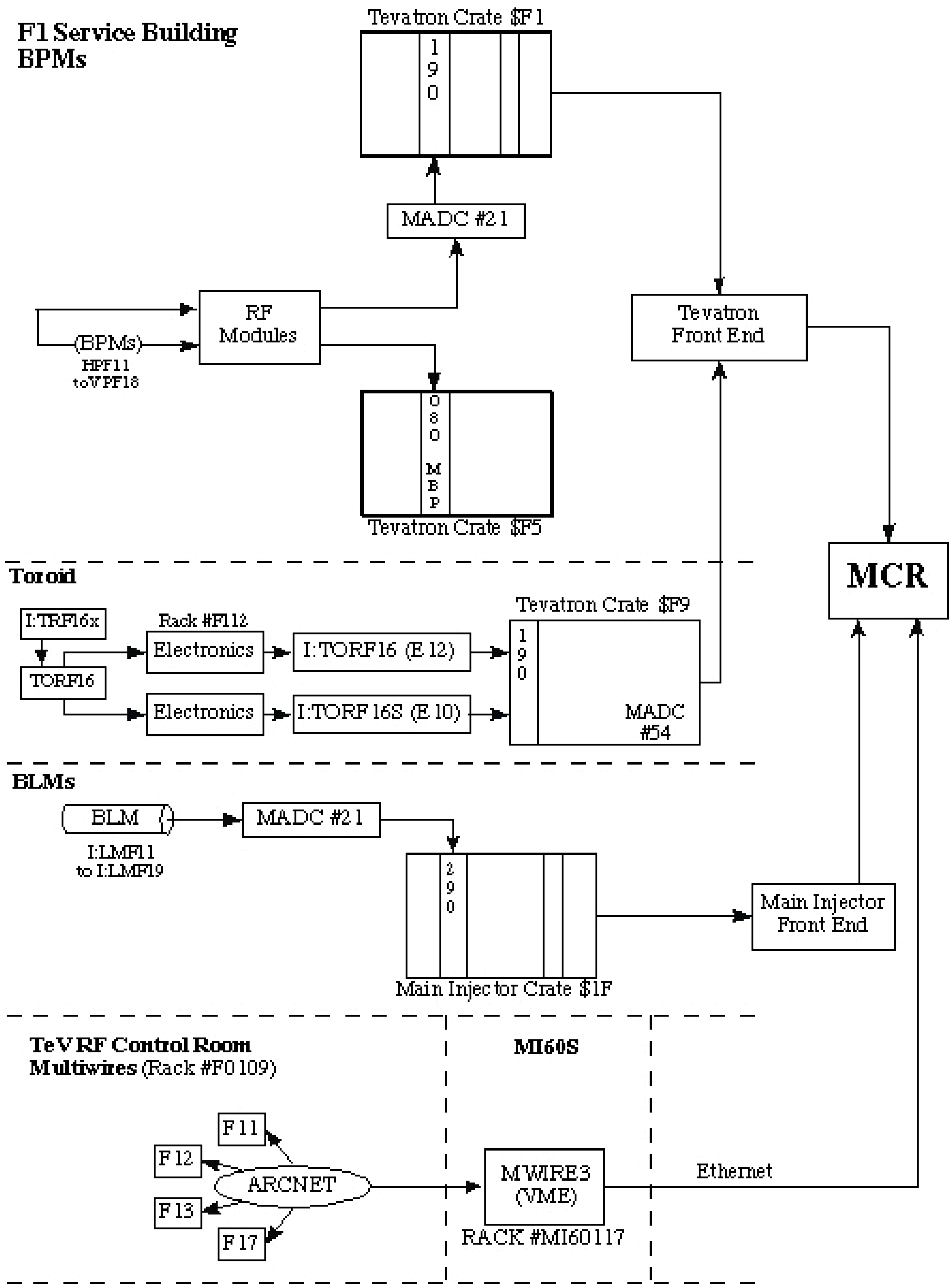


Fig. 7-27 P2 Line Diagnostics

The BPMs in the P2 line can be viewed on I39, either by themselves or in conjunction with the P1 or AP-1 lines. They rely on the same timers as the P1 line. The same is true of the BLMs.

There are five multiwires in the P2 line: (1) upstream of QF11A; (2) downstream of QF12; (3) downstream of QF13; (4) downstream of QF16; and (5) between QF17 and F17B3. The last one in particular is essential for establishing positions going into the AP-1 line. Like the P1 multiwires, the P2 multiwires are controlled from a card in the MWIRE3 crate.

There is one toroid in the P2 line, at F16 (Fig. 7-25). Like the P1 line toroids, the raw signal is sent to two amplifiers. I:TORF16 is scaled in units of E12, and I:TRF16S in units of E10.

The A1 Line

The A1 line has but one purpose: to extract 150 GeV antiprotons from the Main Injector and get them into the Tevatron (Figs. 7-28, 1-11).

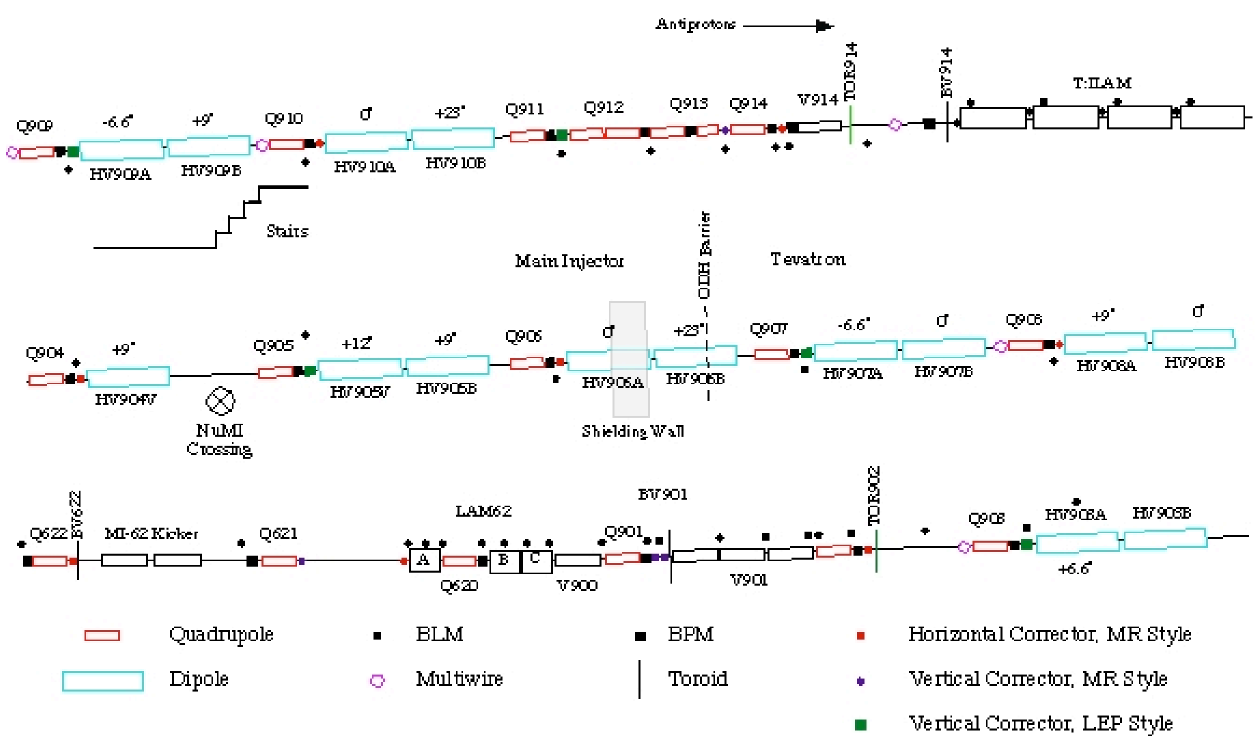


Fig. 7-28 Vertical Profile of the A1 Line

In many respects the A1 line is a mirror image of the P1 line, although the design is simplified by the fact that the beam has only one destination (the Tevatron) and one energy (150 GeV). (This simplicity is somewhat disrupted by the process of reverse injection, to be described below. But the sole purpose of reverse injection is to tune the A1 line for antiprotons at 150 GeV.)

Device names in the A1 line are brought to you by the number “9” (I:, that is).

During shots to the Tevatron, antiprotons are extracted from the Accumulator and sent down the AP3/AP1 lines. They enter the P2 line at F17B3 and transfer to the P1 line at the Tevatron Injection Lambertsons, which have to be off. After they enter the Main Injector from the P1 line, they are accelerated to 150 GeV and coalesced. The kickers at MI-62 fire to extract the beam into the A1 line. The A1 line, which looks remarkably like the P1 line, transports the beam to the Injection Lambertsons (which now have to be on) and on into the Tevatron. The E48 kicker cancels out the horizontal injection angle in the Tevatron. The Main Injector tasks in this process are initiated by a $2A event, and Tevatron events by a $40.

During shot setup, it may take several passes of beam to tune the A1 line. Rather than consume rare antiprotons during this time, reverse injection is used to send protons, going backwards through the line, to accomplish the same purpose. First, protons are accelerated and coalesced in the Main Injector and injected into the Tevatron via the P1 line. $2B and $4D events are used to load the protons, just as if setting up for a proton store. The protons circulate in the Tevatron for a short while; then the E48 kicker is fired to extract the beam. The beam enters the Injection Lambertsons, which bend the beam down into the A1 line. At the end of the line, the kickers at MI-62 are used to close the beam in Main Injector (instead of extracting the beam, as they would for forward antiprotons). A clean pass through the A1 line, and closure in the Main Injector, bodes well for a subsequent beam of antiprotons going the other way.

A $2A/$5D combination is used to orchestrate reverse injection. The $2A ramps the Main Injector to 150 GeV, and the $5D references such things as the transfer switches, kicker resets, and beam diagnostics. A completely new beam sync event is created as well—MIBS $D8. I:TMIPX sets the delay from TCLK $5D to generate MIBS $D8. The reflection event is TCLK $55.

The extraction kickers are just downstream (in the antiproton direction) of Q622. The power supply for the kickers, I:KPS62, is located in the MI-62 Service Building (Fig. 7-29). It always charges to a 150 GeV level. The unclamp parameter is K6AUCD. The beam sync delay timer for antiproton transfers, I:MITPBX, is referenced to TCLK $40, the Tevatron event dedicated to antiproton injection. At the end of the delay, MIBS Event $7B is issued, which sends the timing pulse to the Trigger Interface Module. The reflection event for MIBS $7B is TCLK $5B.

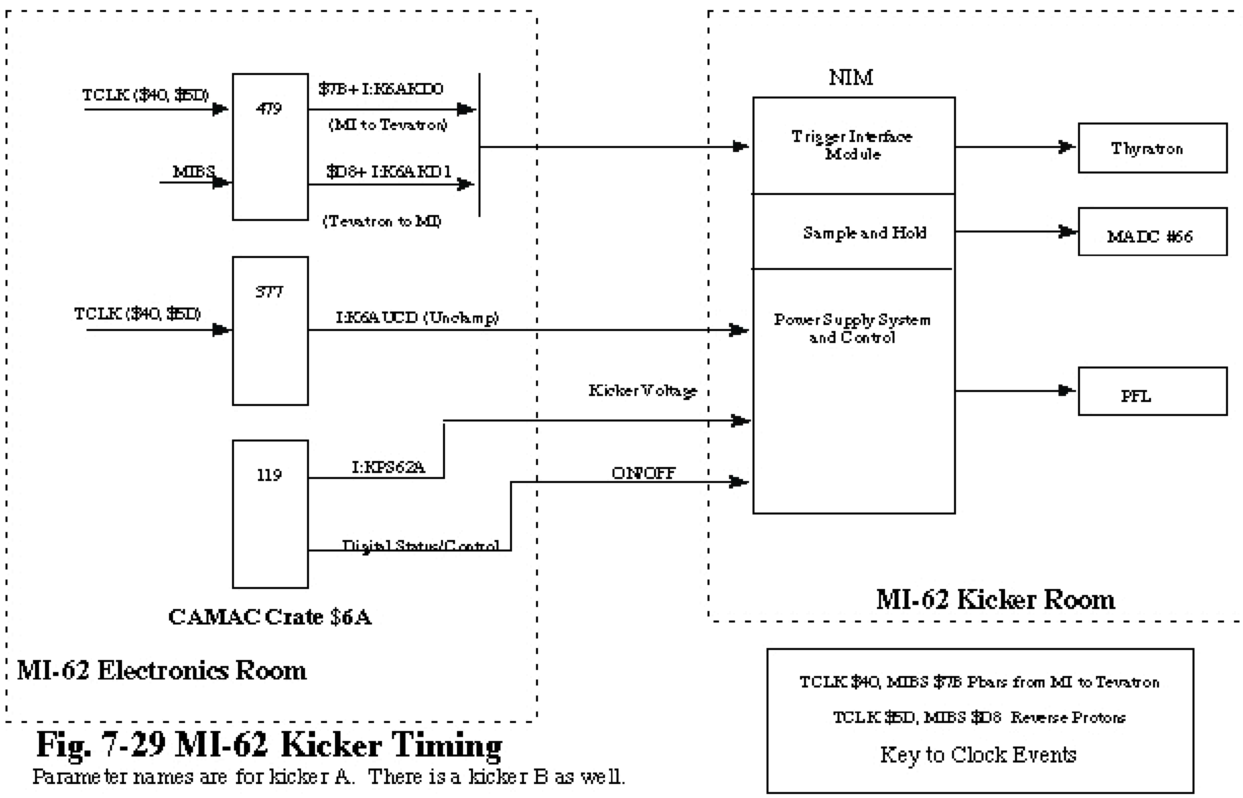


Fig. 7-29 MI-62 Kicker Timing
Parameter names are for kicker A. There is a kicker B as well.

The MI-62 Lambertsons form the usual 3-magnet cluster, this time around Q620. They bend beam up and out from the Main Injector. All three are powered.

The C-magnets, V900 and V901, are analogous to V700 and V701; V900 bends the beam up and the three magnets of V901 reduce the upward angle. (After the C-magnets, as in the P1 line, a series of 84” quads and rolled B2 dipoles takes the beam up and out toward T:ILAM. (The second would-be dipole between Q904 and Q905 is missing, in order to let the NuMI line pass through.) Toward the end of the line, Q911 through Q914 form a matching lattice to the Tevatron, which happens to be where the beam is headed. Then, as with 150 GeV protons, the Tevatron Injection Lambertsons are used to cancel the upward motion of the beam. Finally, the beam is closed horizontally in the Tevatron with the E48 kicker.

Power Supplies

The supplies for LAM62 and V901 are P=EI supplies. The extraction Lambertson is powered by I:LAM62. Miraculously, there are no transfer switches involved, because of the constant energy of extracted beam. I:V901 is actually powered by two P=EI supplies, I:V901A and I:V901B.

All of the magnets downstream of V901 are powered from the same supplies as their counterparts in the P1 line (Fig. 7-23). The alert reader will recognize a dilemma here—during shots, the P1 line magnets are needed to get particles in to the Main Injector at 8 GeV, but seconds later, the A1 line magnets are needed to transfer 150 GeV beam to the Tevatron. This is where a set of transfer switches is needed.

The switch between the two beam lines is sent from two parameters: I:LSPON and I:LSAON, in the case of quadrupoles, and I:LSPON2 and I:LSAON2 for the dipoles. For example, I:Q701 powers Q701 in the P1 line and Q901 in the A1 line. During shot setup, these parameters are referenced to TCLK $40 (forward antiprotons) or $5D (reverse protons), which are issued simultaneously with the $2A event.

The default state is for the P1 devices to be powered. As of this writing, antiprotons are sent to the Main Injector through the P1 line at about 1.6 seconds after the $2A. Then the 465 tables ramp down to zero output; I:LSAON and I:LSAON2 are issued 2.2 seconds after the $2A. At that point, the transfer switch physically disconnects the P1 line magnets from their power supplies and connects the supplies to the A1 line magnets. Beam begins accelerating around 4.5 seconds, is coalesced at flattop, and injected into the Tevatron via the A1 line at 6.7 seconds. At the end of the ramp, around 7.8 seconds, the tables again go to zero, I:LSPON and I:LSPON2 are issued, and the P1 magnets are reconnected, ready for the next cycle.

From the CAMAC perspective, the 468 cards servicing the P1 magnets also cover the corresponding magnets in the A1 line—Ramp "E" is usually referenced to a $40 and $5D to handle Pbar injection and reverse injection. As with the P1 line devices, page I68 is normally used to tune the line (except for closure).

Since the beam in the A1 line is always at 150 GeV, it is possible to use the high-inductance LEP dipoles; they are found at all of the vertical locations except for 901 and 913, which use Main Ring style dipoles. The horizontal correctors are all of the Main Ring style. The A1 corrector regulators are tied into CPS6N, as are some of the P1 correctors (Fig. 7-30).

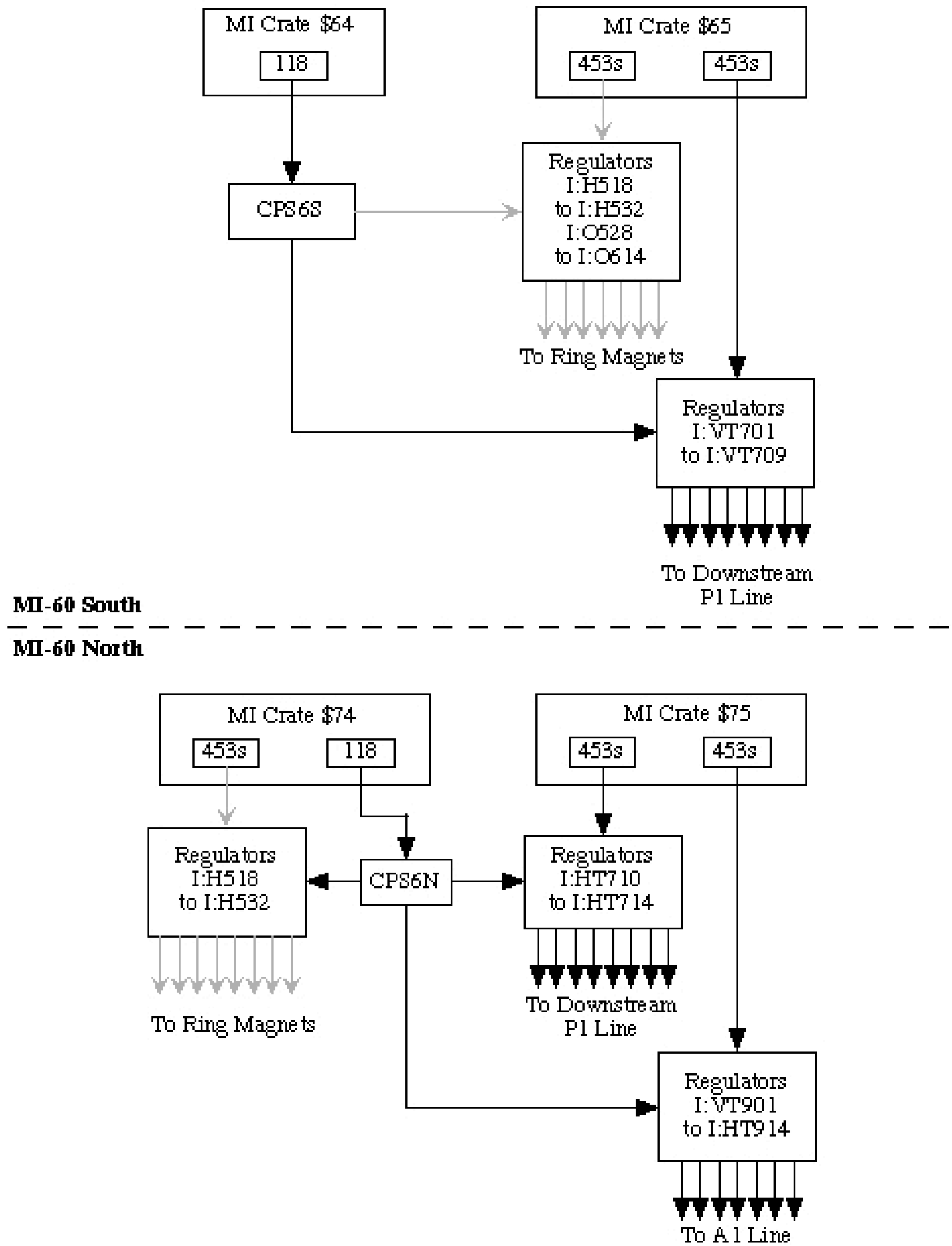


Fig. 7-30 P1 and A1 Corrector Dipole Power Supplies

The dipole correctors in the P1 and A1 lines use the same bulk power supplies as the ring correctors

LCW

Although the A1 line components are nearly identical to those in the P1 line, they do not require quite as much cooling. That is because they are only used during Pbar transfers and reverse injection, and at a relatively low rep rate. A stand-alone system like the one at MI-52 is not required. The LCW branches off of the ring headers at the C-magnets and begins feeding the A1 line components at Q903.

At the MI-62 service building, there is a branch coming up from the tunnel to feed the power supplies for V901 and LAM62.

Vacuum

The extraction region into the A1 line is bounded by three valves — BV622 and BV619 isolate the short straight section, while BV901 isolates the beam line just downstream of the Lambertson magnets. The downstream end of the beam line is isolated from the injection Lambertsons by BV914. Ion pump and Penning gauge status can be read under "Beam Lines/A150" on page I55. The vacuum hardware can be found at MI60N, under the name "150 GeV Line." Included are a CIA crate and ion pump power supplies.

Beam Diagnostics

The A1 line beam diagnostics (Fig. 7-31) are nearly symmetrical with those in the P1 line, but somewhat simplified by having only two modes of operation: antiproton extraction to the Tevatron, and reverse injection ($40 and $5D, respectively). They include:

- Multiwires (MW902 to MW914), which are controlled through an ARCNET loop originating from the VME MWIRE3.
- BPMs (HP902 to VP914), which report through the VME IBPMA1.
- BLMs (LM901 to LMAC2D), which can be read back through MADC channels; readbacks are also sent to IBPMA1 so that an integrated picture of losses and beam positions can be assembled.
- Toroids at 902 and 914, which are read through MADCs.

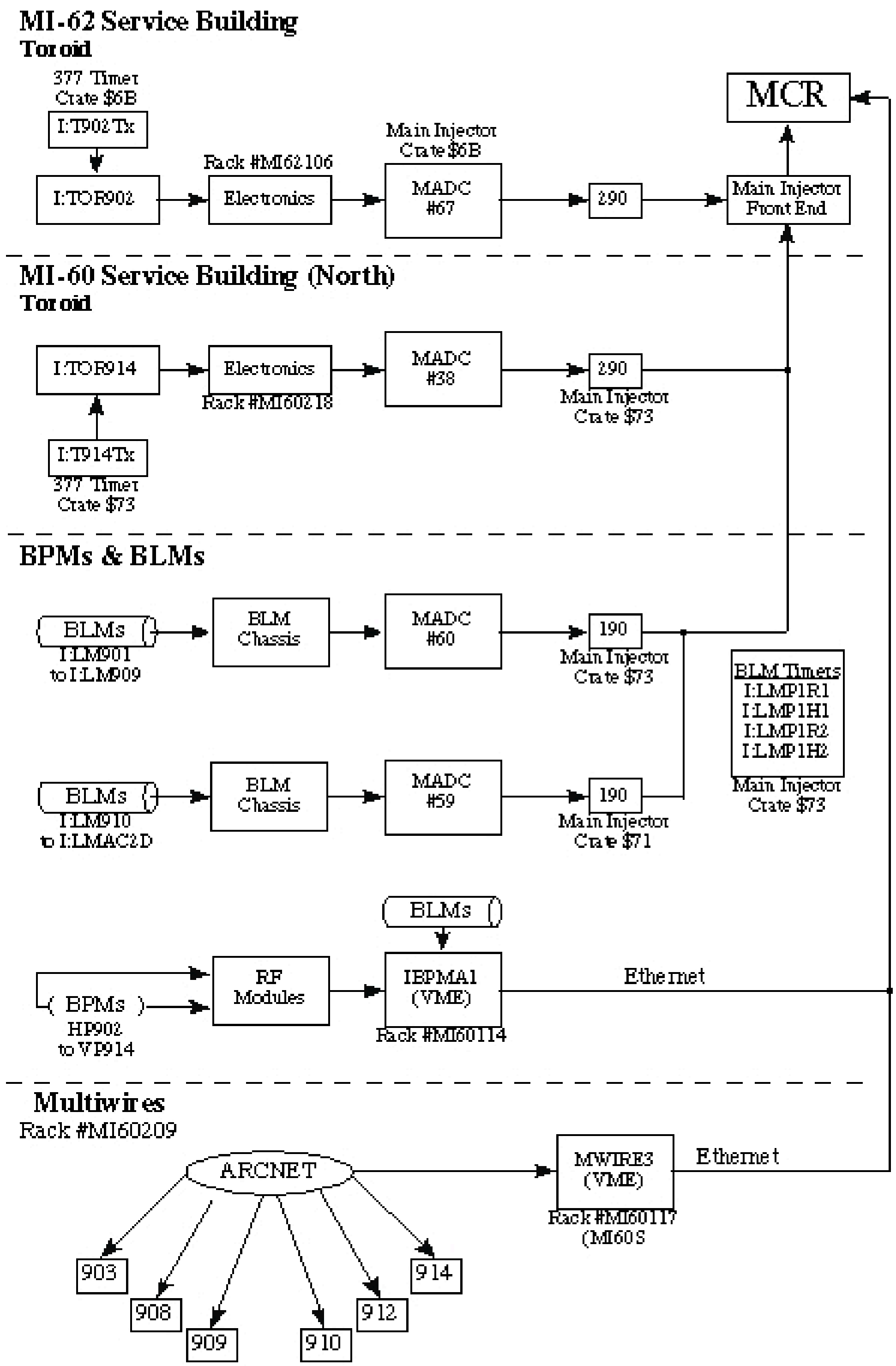


Fig. 7-31 A1 Line Diagnostics

The Recycler

Antiprotons from the Recycler enter the Main Injector at MI-22 and are extracted at MI-32; permanent magnet Lambertsons at 321 and 222 bends the beam appropriately. There is a single kicker at 304, in the MI-30 long straight section, that either kicks the beam into the field region of one of the Lambertsons or kicks the beam onto a closed orbit in the Main Injector, as needed:

[Embedded schematic of transfer]

There are, of course, also kickers and Lambertsons in the Recycler ring itself. For reasons of economy, the extraction kicker for antiprotons is also the abort kicker.

[Clock events]

NuMI

The initial extraction to NuMI is virtually identical to the standard used by the P1 and A1 lines. Extraction is from the MI-60 straight section—there is a stretch of space available just downstream of the coalescing cavities. There is a kicker just downstream of Q606, while the three Lambertsons are clustered around Q608 and Q609. Although the beam is eventually destined to plunge deep into the earth, where no beam has gone before, C-magnets raise the beam up over the Main Injector magnets so that it can be transported toward the NuMI stub.